STAR

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Jets at STAR

Hot Jets: Advancing the Understanding of High-Temperature QCD with Jets

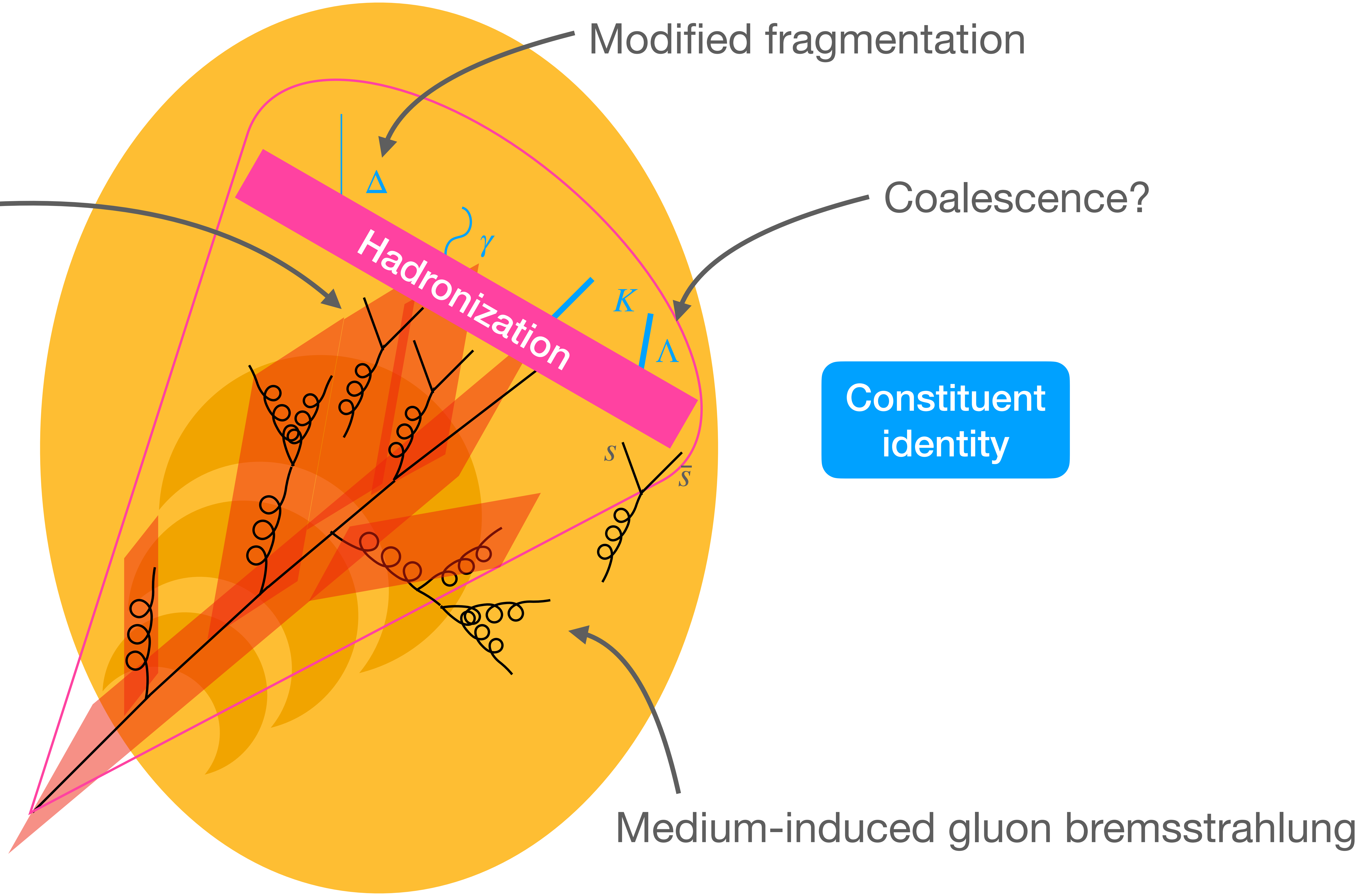
University of Illinois, Champaign-Urbana, IL
January 9, 2025

Isaac Mooney (Yale University, BNL) for the STAR Collaboration, isaac.mooney@yale.edu

How to understand jet evolution in media

Two ways: the How and the What

Energy flows



Constituent identity

Solenoidal Tracker at RHIC (STAR)

Image: NSWW

Main subdetectors, as of mid-2010s

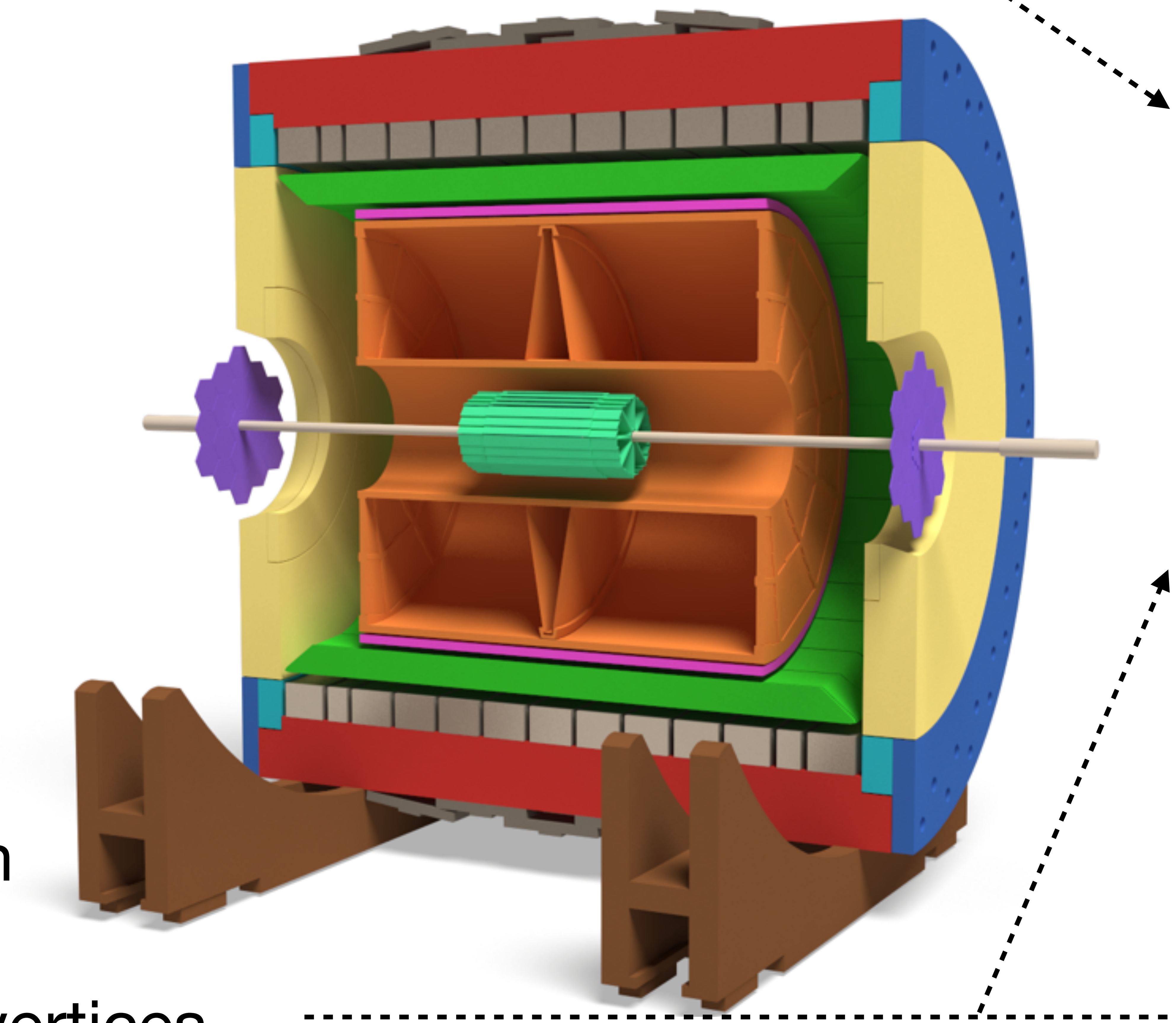
Relativistic Heavy Ion Collider (RHIC) collides *p*+*p*, isobars (Zr+Zr, Ru+Ru), Au+Au, etc. from $\sqrt{s_{\mathrm{NN}}} = 3$ to 510 GeV

Time Projection Chamber (TPC) [$|\eta| < 1$]: momenta of charged tracks + centrality + PID

Barrel Electromagnetic Calorimeter (BEMC) [$|\eta| < 1$]: neutral energy deposits + online trigger

Time of Flight (TOF) [$|\eta| < 0.9$]: PID + pileup mitigation

Heavy flavor tracker (HFT) [$|\eta| < 1$]: displaced decay vertices



Precision QCD; exploring the Lund plane with *multi-dimensional jet substructure*

Path-length dependence of jet energy loss in medium with *jet anisotropies (with respect to event plane)*

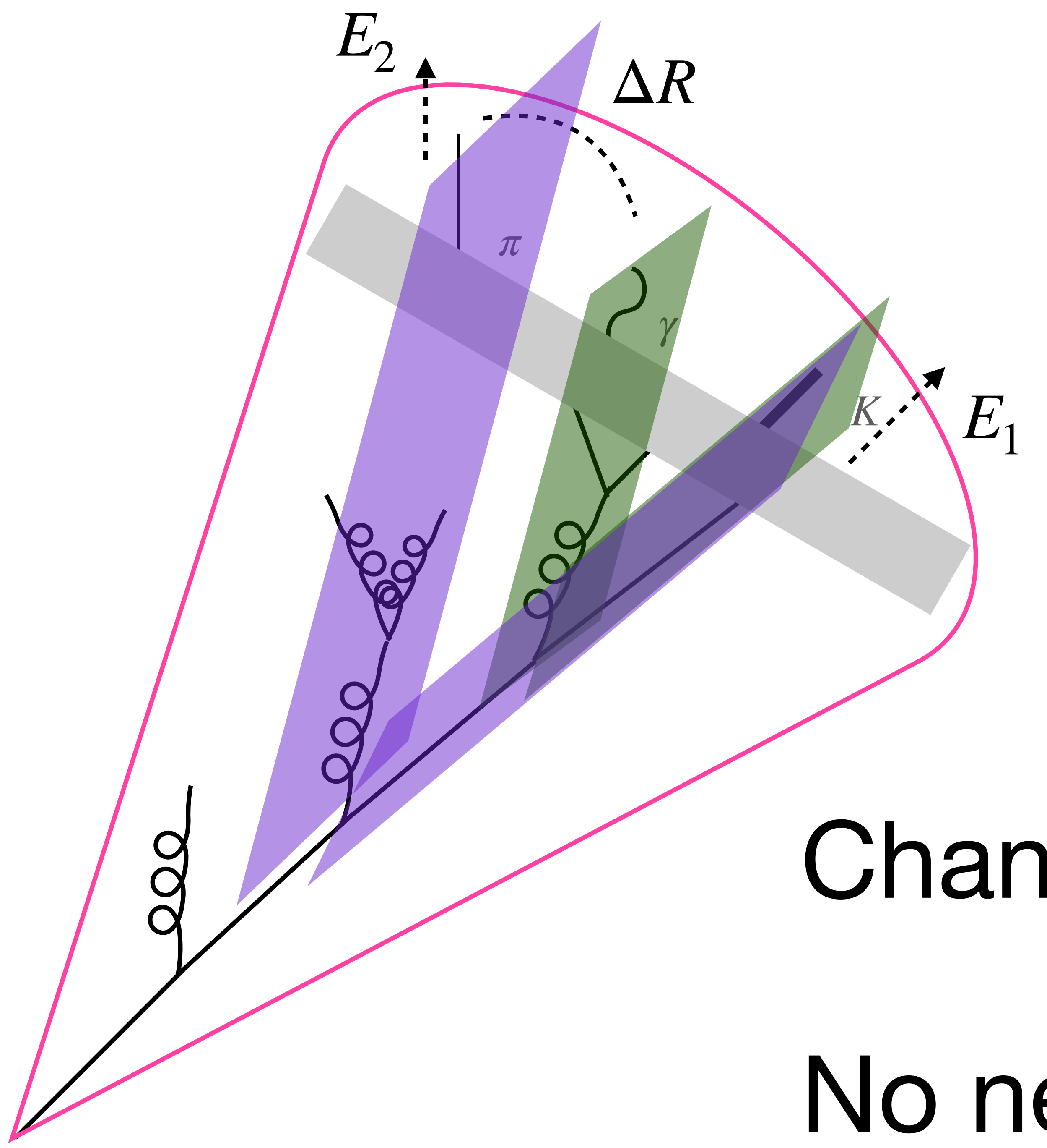
Separating p-QCD and np-QCD with *energy correlators*

Energy flows

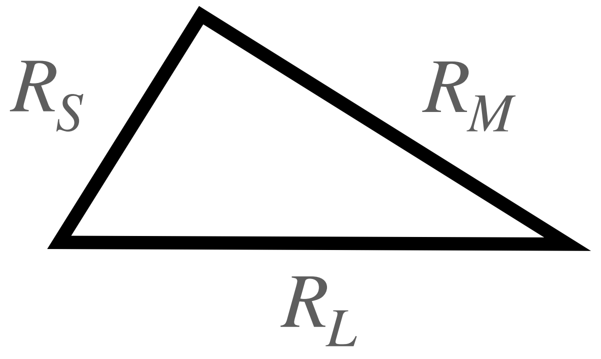
Energy-density dependence of jet energy loss in medium; angular distribution of radiation in quenched jets with *inclusive/semi-inclusive jet & high-p_T hadron yields*

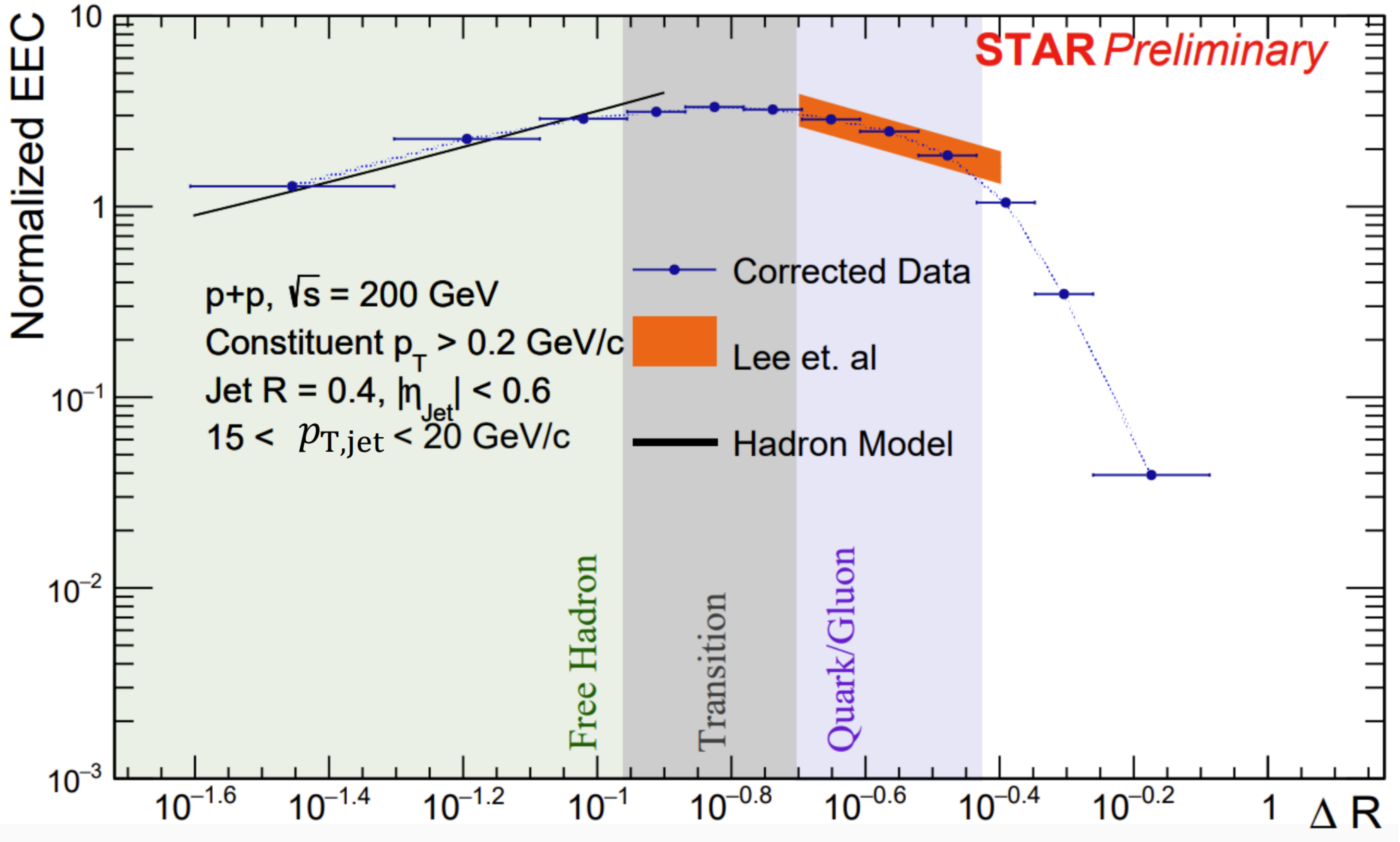
Energy correlators

$$\text{ENC}(R_L) = \left(\prod_{k=1}^{N}\int d\Omega_{\vec{n}_k}\right)\delta\left(R_L - \Delta\hat{R}_L\right)\frac{1}{\left(E_{\text{jet}}\right)^N}\left\langle \mathcal{E}(\vec{n}_1)\,\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\right\rangle$$ [1,2,3]



$$\text{EEC}(\Delta R) = \frac{1}{\mathcal{O}}\frac{d\mathcal{O}}{d(\Delta R)},\ \mathcal{O} = \sum_{\text{jets}}\sum_{i\neq j}\frac{E_iE_j}{p^2_{\text{T,jet}}}$$





Change in scaling when virtuality $\sim p_T R_L \sim \Lambda_{\text{QCD}}$ so $R_L^{\text{transition}} \propto 1/p_T$

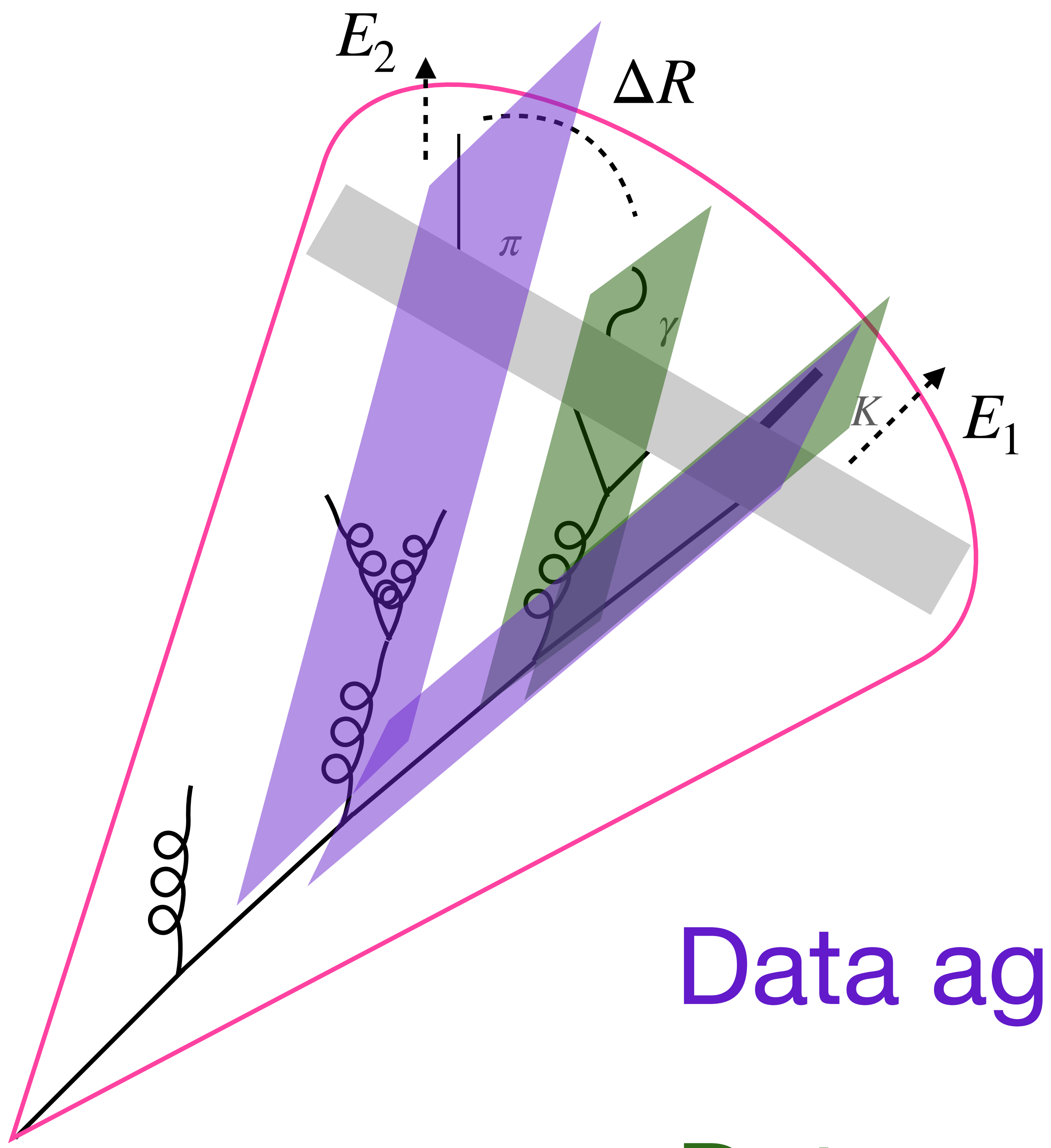
No need to recluster or remove npQCD contributions

Simple scaling in the hadronic and partonic regimes

[1]Basham, Brown, Ellis, Love, PRL 41 (1978), 1585
[2]Chen, Moult, Zhang, Zhu, PRD 102 (2020) 5, 054012
[3]Komiske, Moult, Thaler, Zhu, PRL 130 (2023) 5, 051901

Energy correlators

$$\text{ENC}\left(R_L\right) = \left(\prod_{k=1}^{N}\int d\Omega_{\vec{n}_k}\right)\delta\left(R_L - \Delta\hat{R}_L\right)\frac{1}{\left(E_{\text{jet}}\right)^N}\left\langle \mathcal{E}\left(\vec{n}_1\right)\mathcal{E}\left(\vec{n}_2\right)\ldots\mathcal{E}\left(\vec{n}_N\right)\right\rangle$$ [1,2,3]



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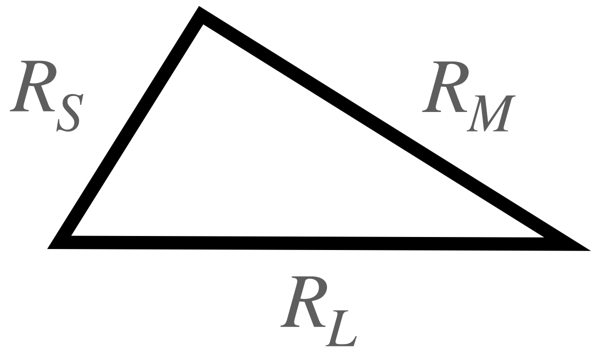

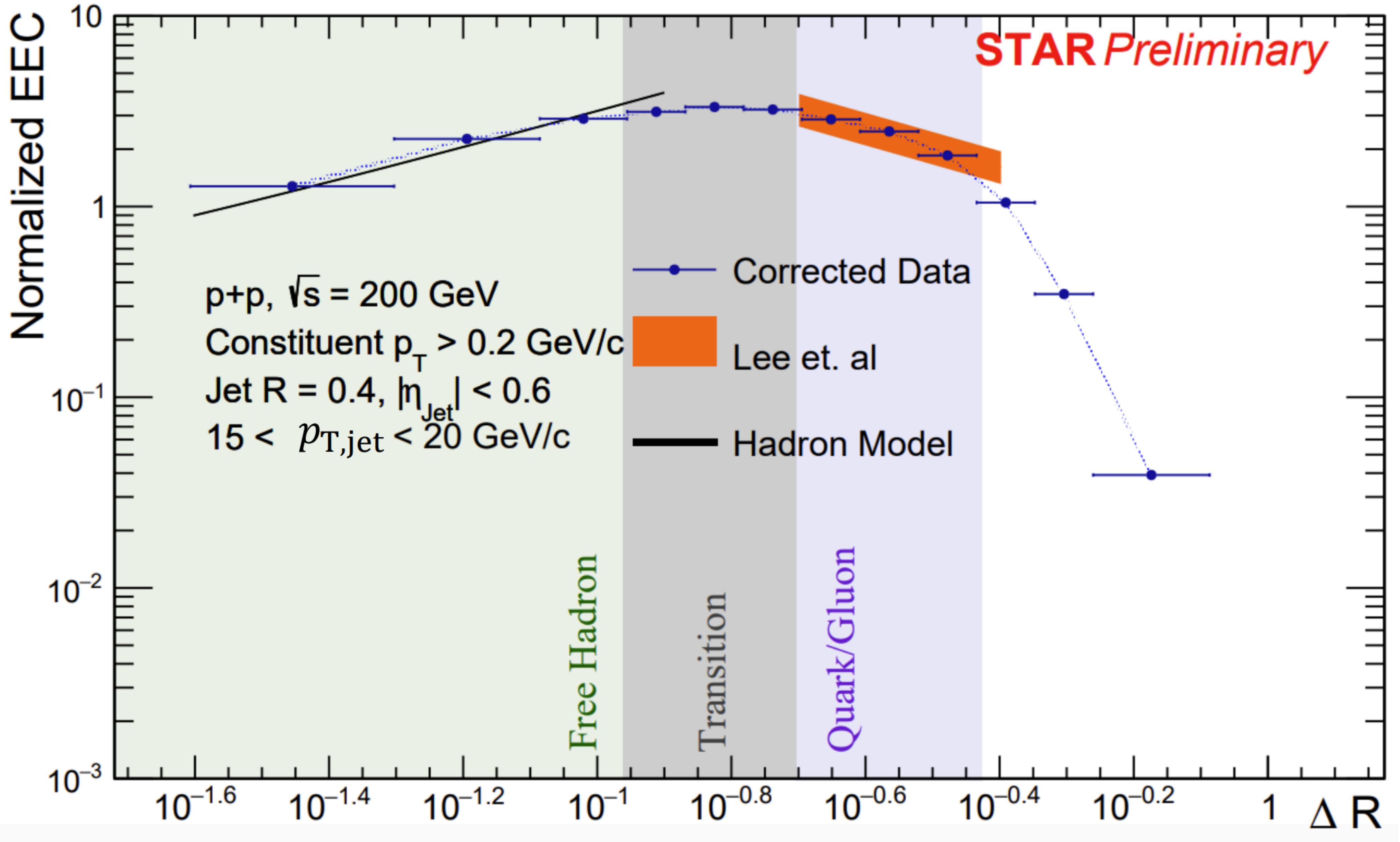

Data agree well with NLL pQCD calculation* (& MC model, not shown)

Data agree well with model assuming non-interacting hadrons

[1] Basham, Brown, Ellis, Love, PRL 41 (1978), 1585
[2] Chen, Moult, Zhang, Zhu, PRD 102 (2020) 5, 054012
[3] Komiske, Moult, Thaler, Zhu, PRL 130 (2023) 5, 051901

*Lee, Meçaj, Moult, arXiv:2205.03414

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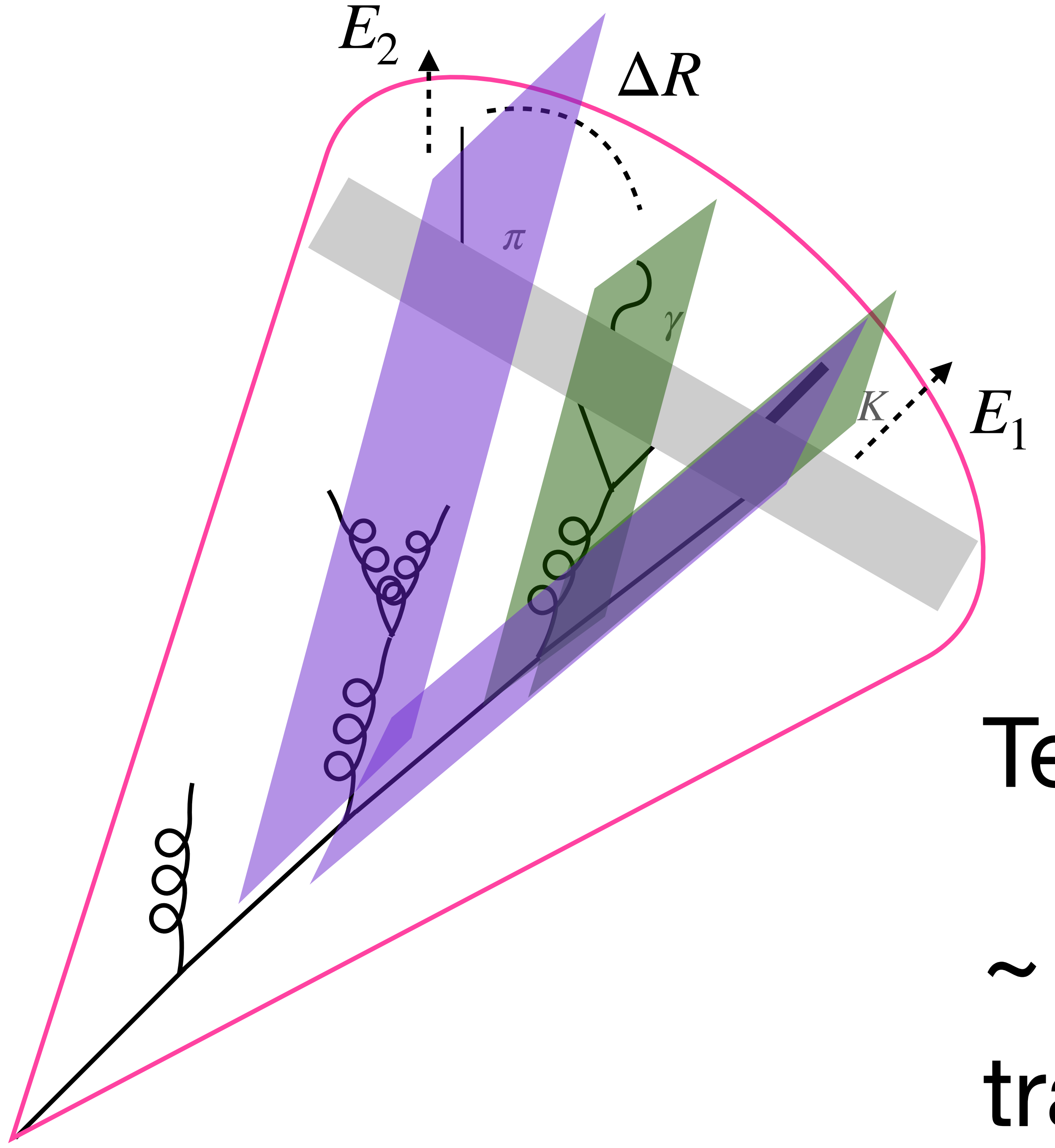

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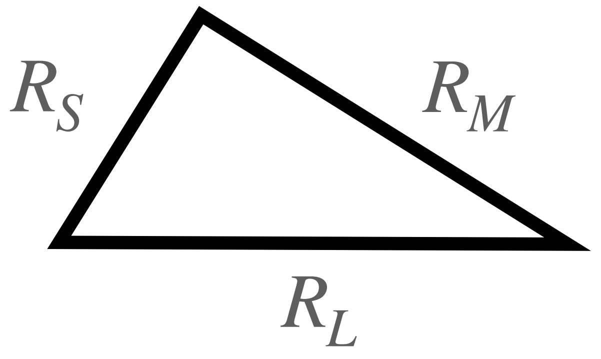

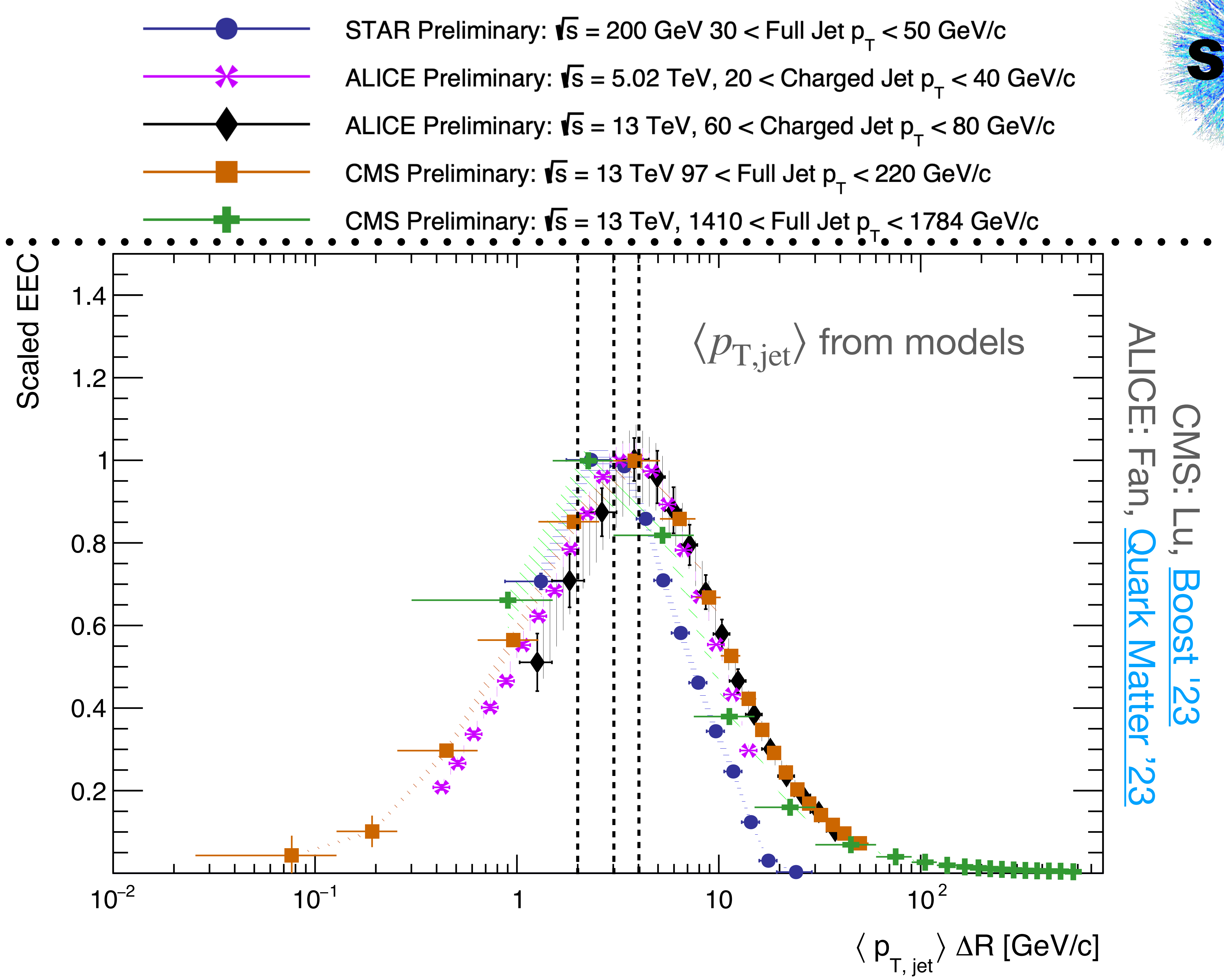

Testing universality of transition region by comparing to LHC data:

~ 2 orders of magnitude in $\sqrt{s}$ and $p_{\mathrm{T,jet}}$ from STAR → ALICE → CMS, transition region ~ 2 – 4 GeV/c

STAR more similar to CMS high-p_T (high-x) jets than ALICE or CMS low-p_T jets — **q vs. g** differences

[1]Basham, Brown, Ellis, Love, PRL 41 (1978), 1585
[2]Chen, Moult, Zhang, Zhu, PRD 102 (2020) 5, 054012
[3]Komiske, Moult, Thaler, Zhu, PRL 130 (2023) 5, 051901

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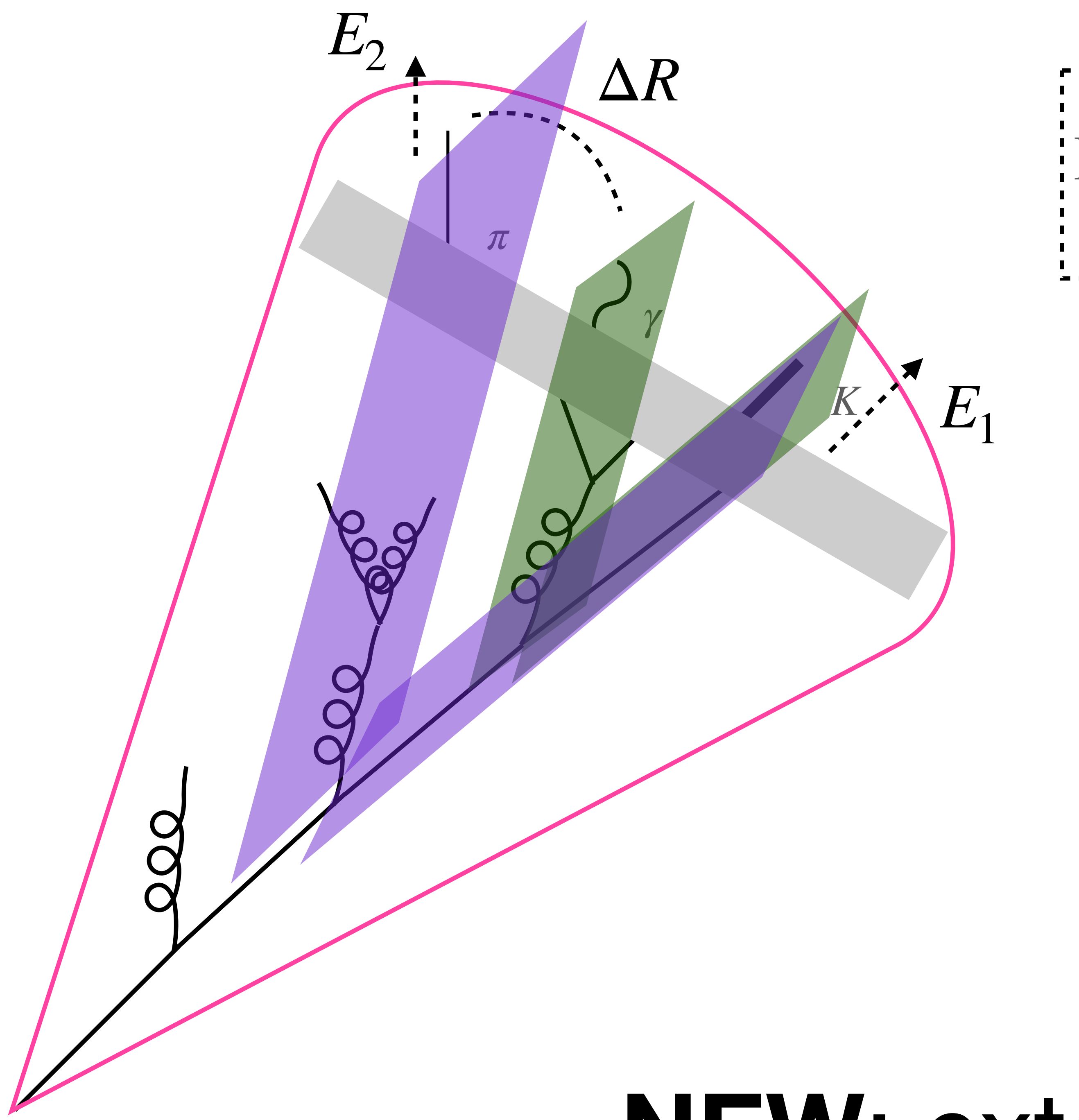

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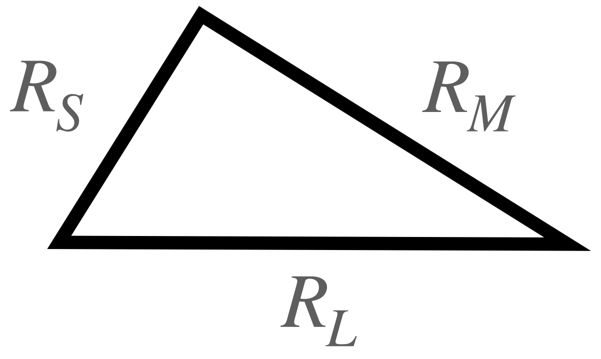
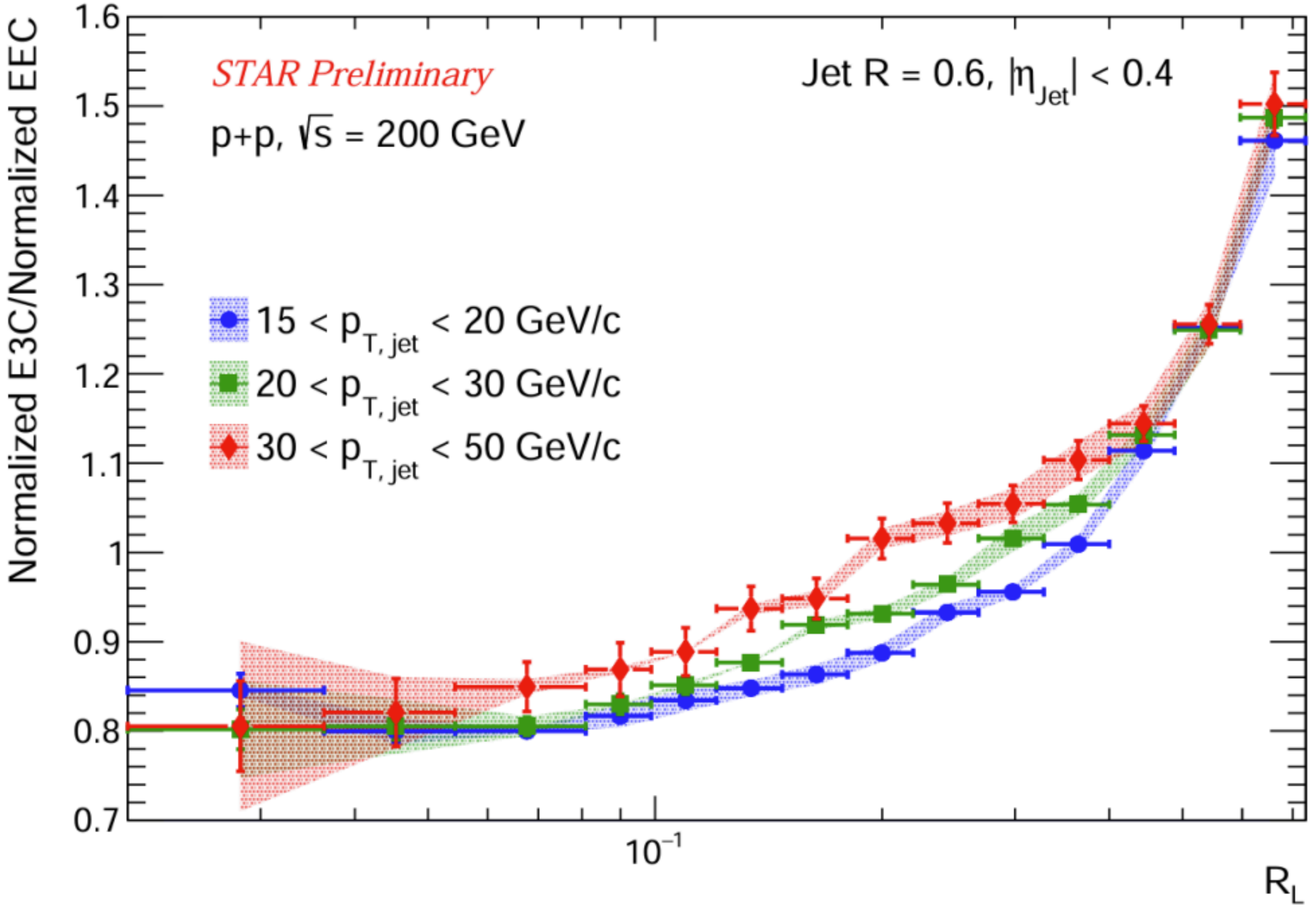


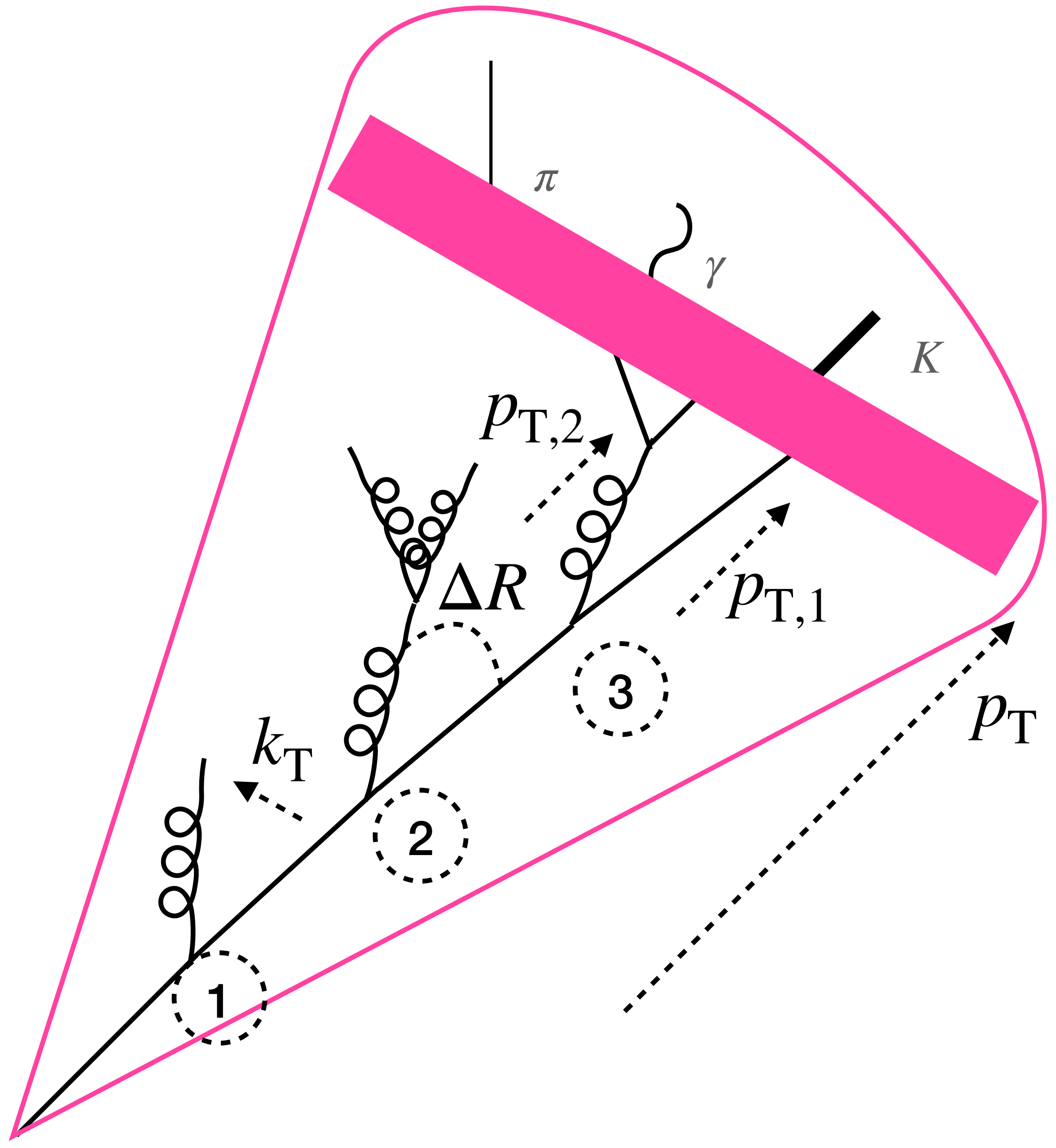


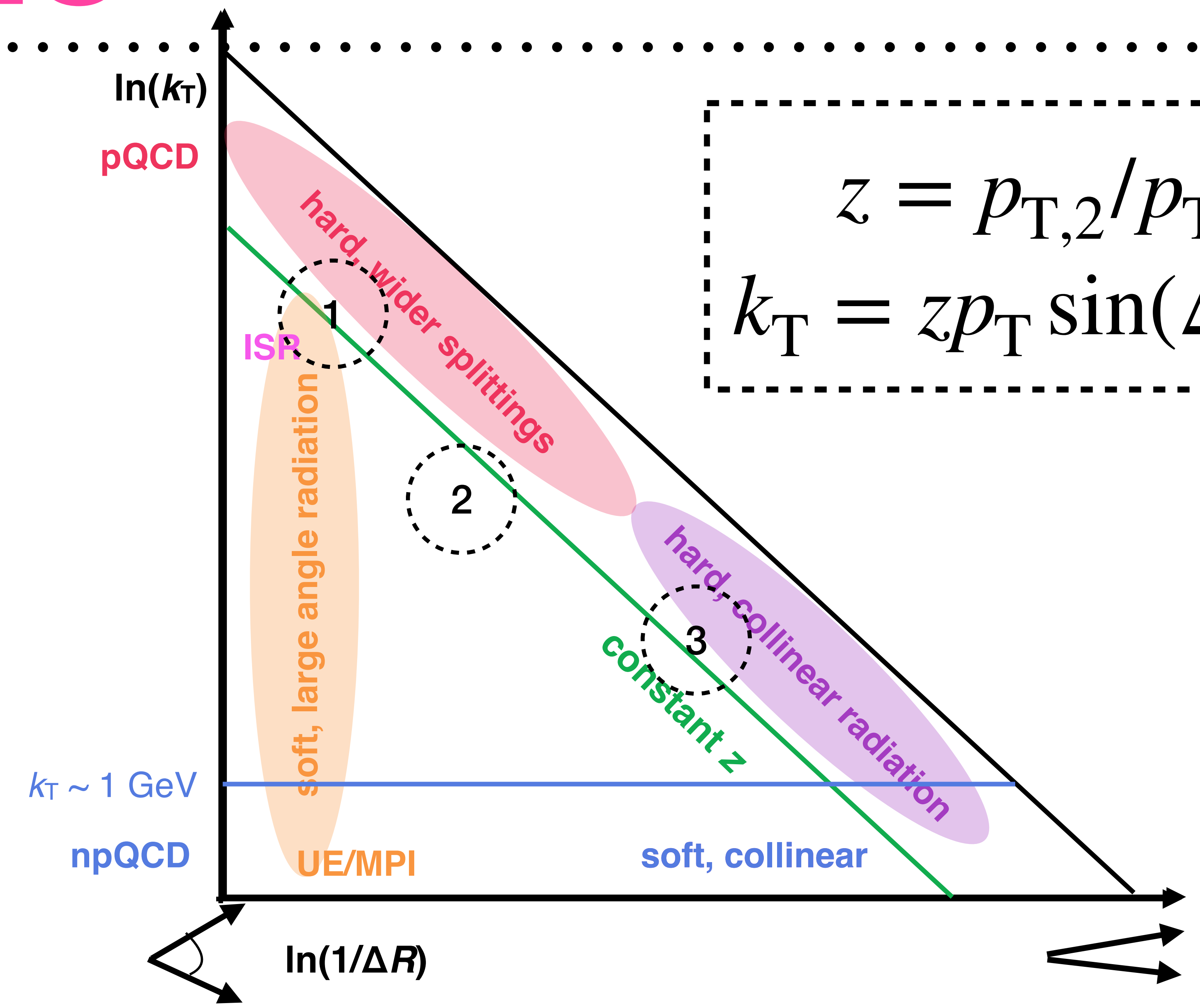
NEW: extended to E3C — running of α_s causes change in slope with p_T*

*Chen, Moult, Zhang, Zhu, PRD 102 (2020) 5, 054012

[1]Basham, Brown, Ellis, Love, PRL 41 (1978), 1585
[2]Chen, Moult, Zhang, Zhu, PRD 102 (2020) 5, 054012
[3]Komiske, Moult, Thaler, Zhu, PRL 130 (2023) 5, 051901

SoftDrop and the Lund Plane



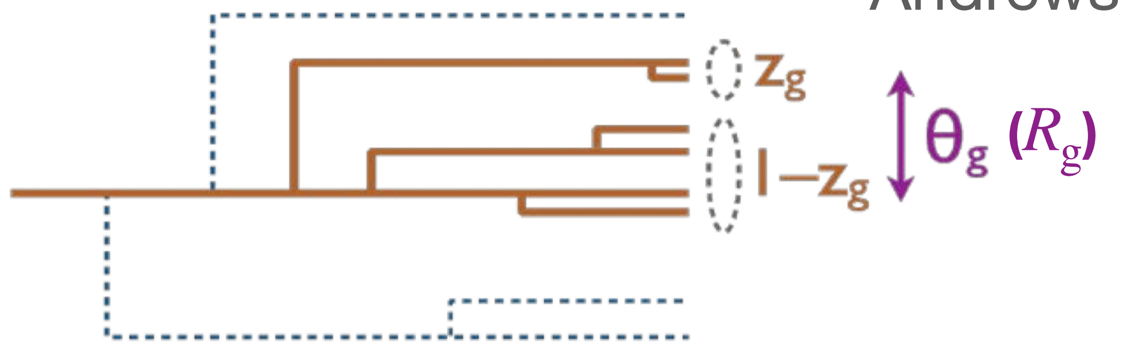


$$z = p_{T,2}/p_T$$
$$k_T = z p_T \sin(\Delta R)$$

Image: Laura Havener, modified from Andrews et al., J.Phys.G 47 (2020) 6, 065102

$$\frac{\min\left(p_{T,i}, p_{T,j}\right)}{p_{T,i} + p_{T,j}} > z_{cut}\left(\frac{\Delta R_{ij}}{R}\right)^{\beta}$$

$$z_g = \frac{\min\left(p_{T,1}, p_{T,2}\right)}{p_{T,1} + p_{T,2}}$$



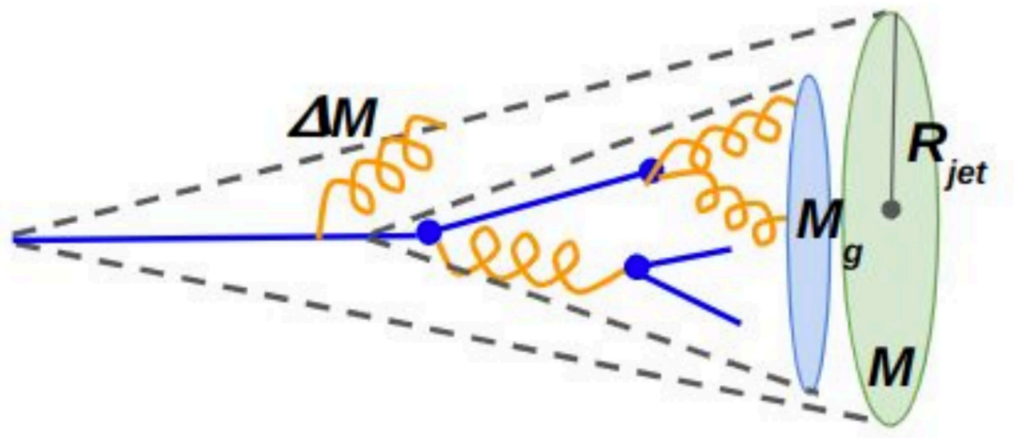
$$M_g = \left|\sum_{i \in J_g} p_i\right|$$

Image: Larkoski, Marzani, Thaler, Xue, PRL 119 (2017) 13, 132003

SoftDrop[1] grooming: reduce soft non-perturbative contribution
→ better theoretical control

[1]Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014), 146

N-dimensional substructure



With MultiFold

$$\Delta M = M - M_g^*$$

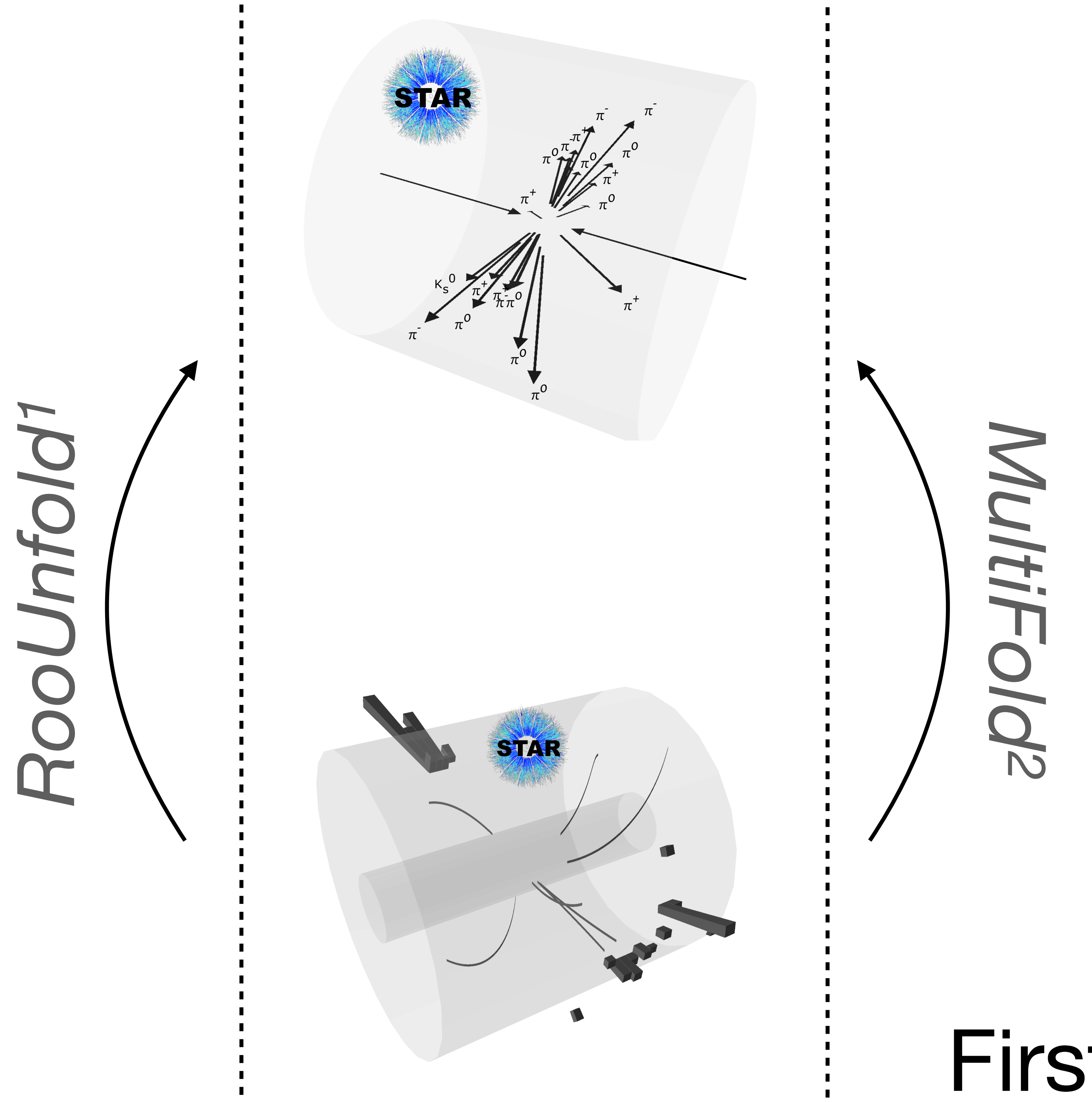
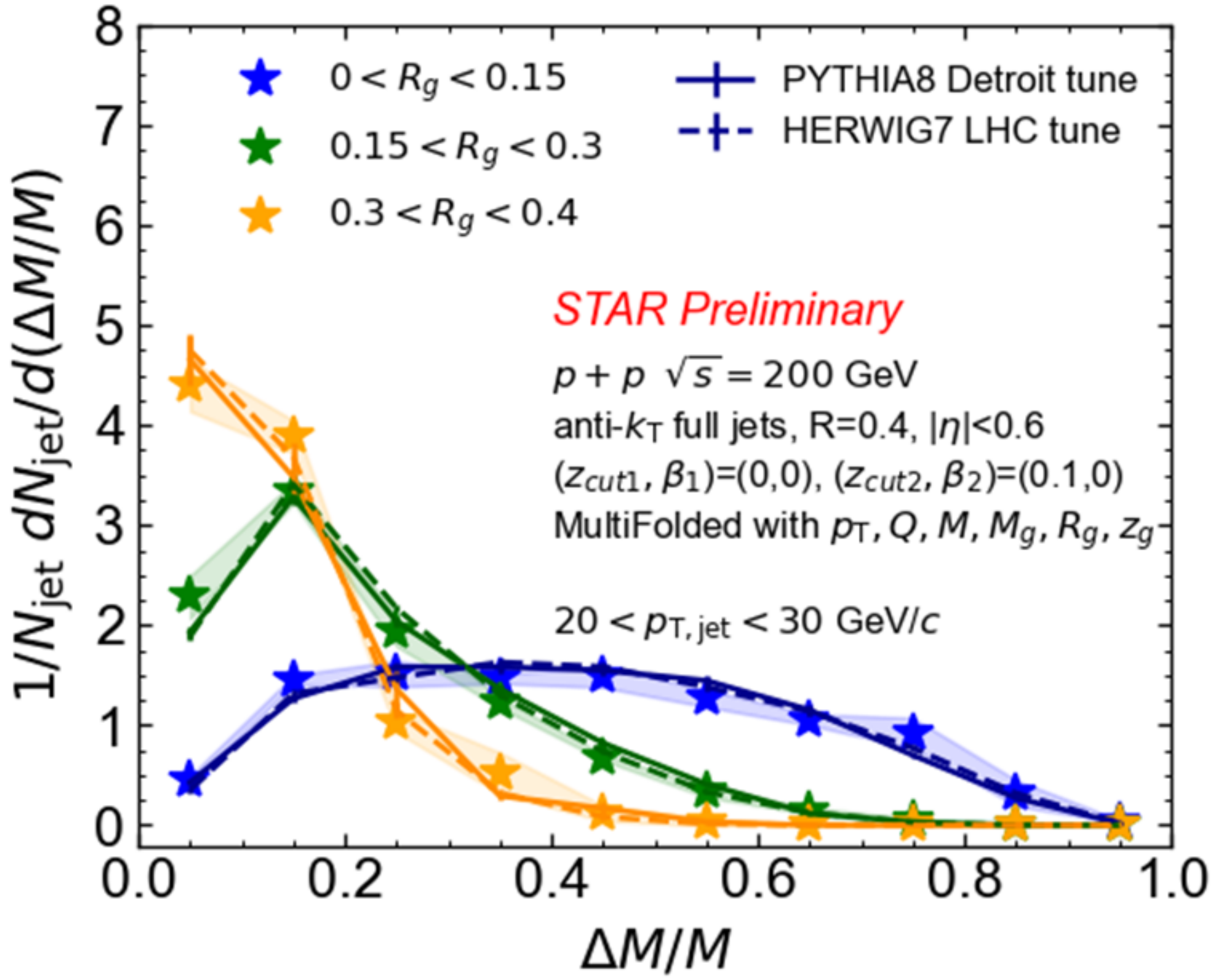
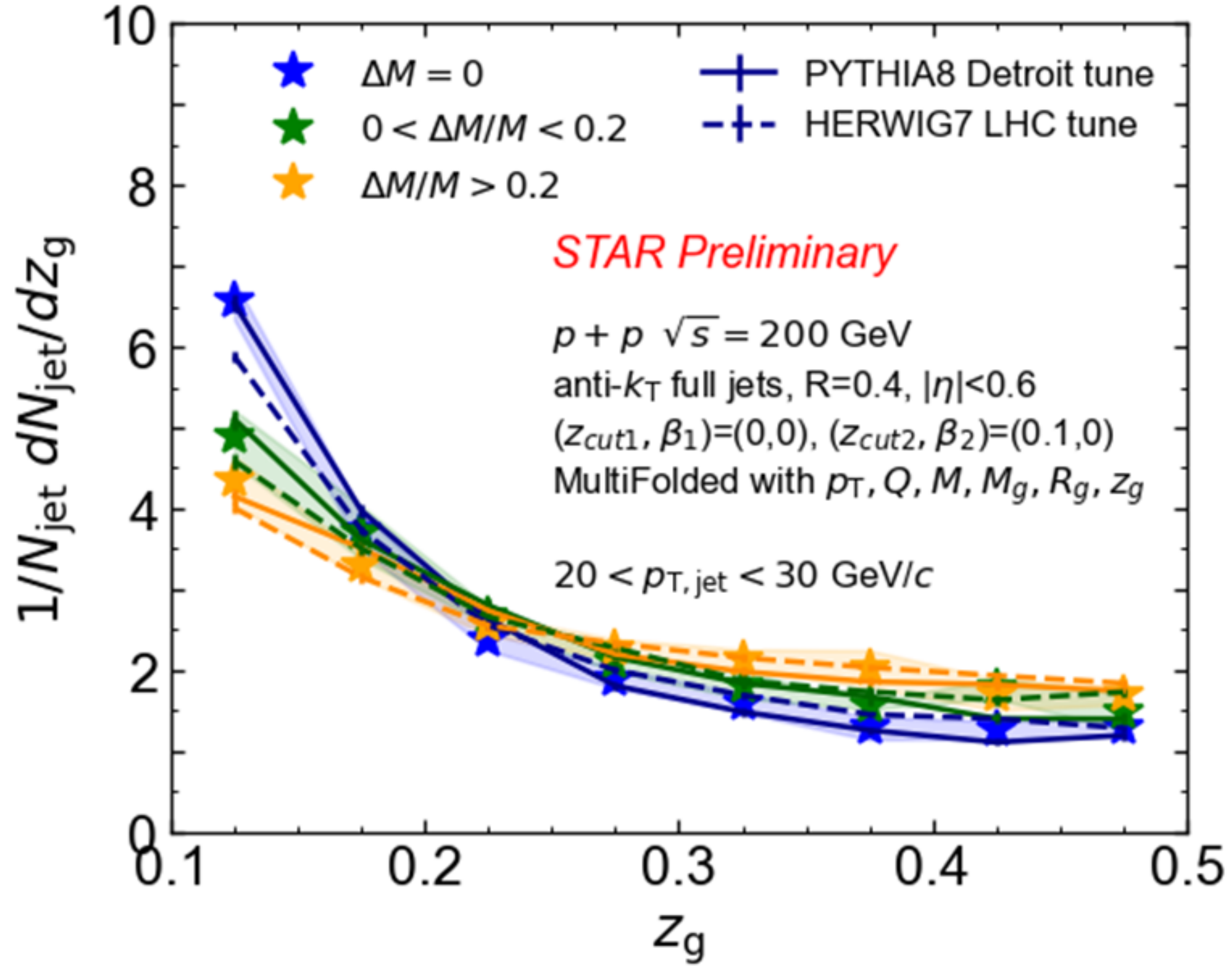


Image: Tai Sakuma





First application of MultiFold at RHIC

Correlation between R_g, z_g and ΔM consistent with angular ordering + kinematic constraint between early and late time splittings

[1]D'Agostini, arXiv:1010.0632

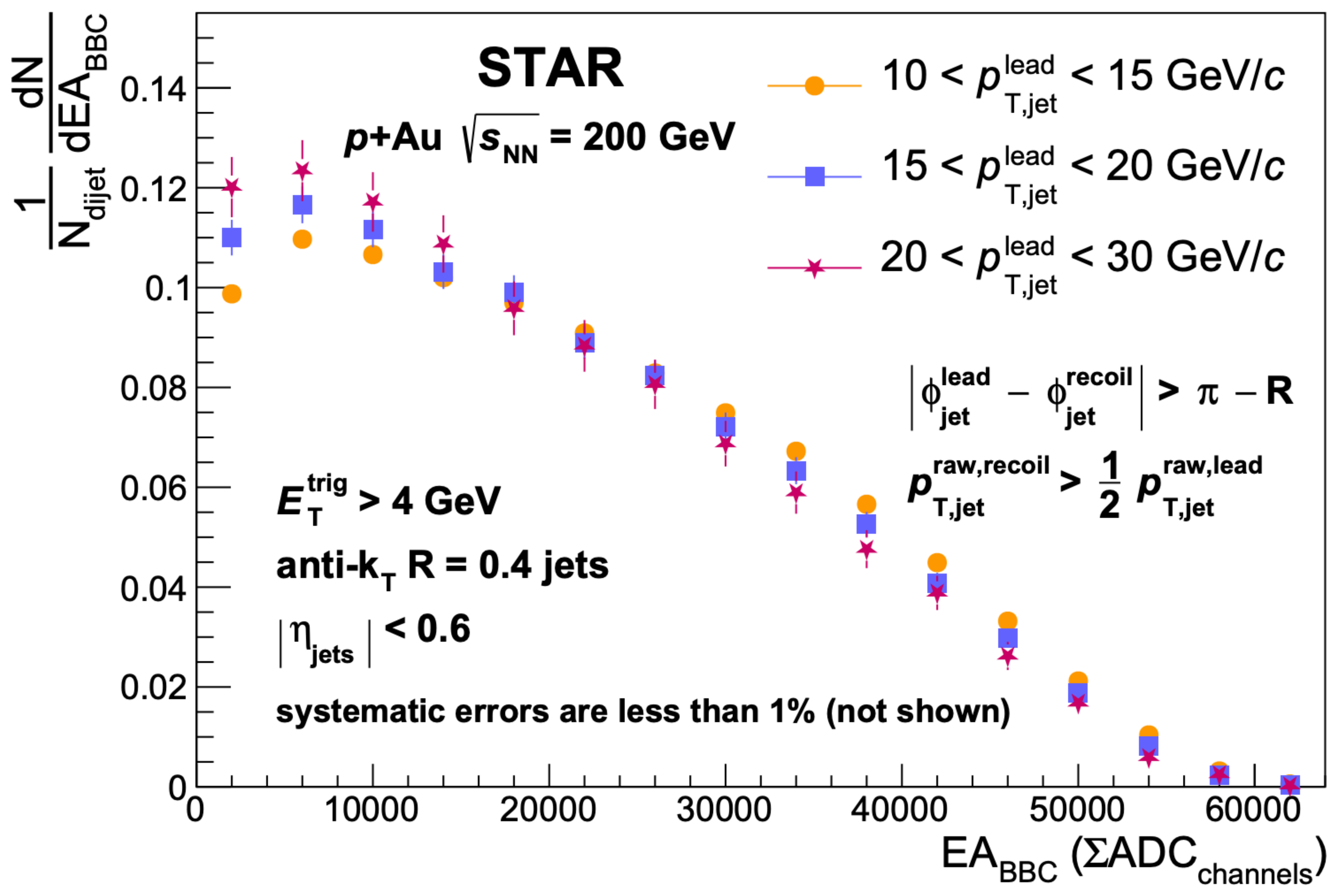
[2]Andreassen, Komiske, Metodiev, Nachman, Thaler, PRL 124 (2020) 18, 182001

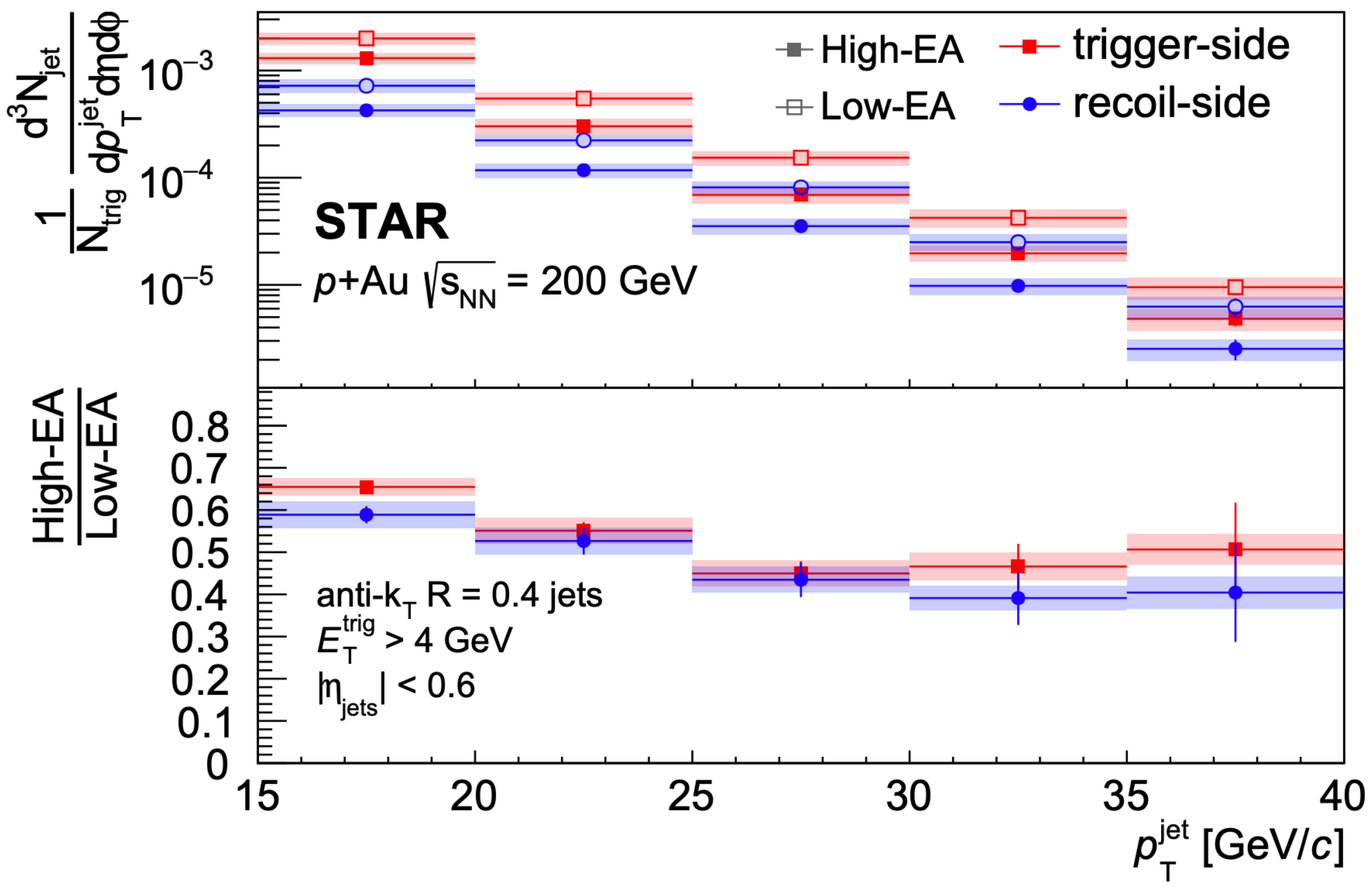
*Chien, Stewart, JHEP 06 (2020) 064

Interlude: quenching in small systems?

Recently published in PRC! — [PRC 110 (2024) 4, 044908]

Short answer: disfavored at RHIC in p+Au collisions by this set of yield measurements from STAR

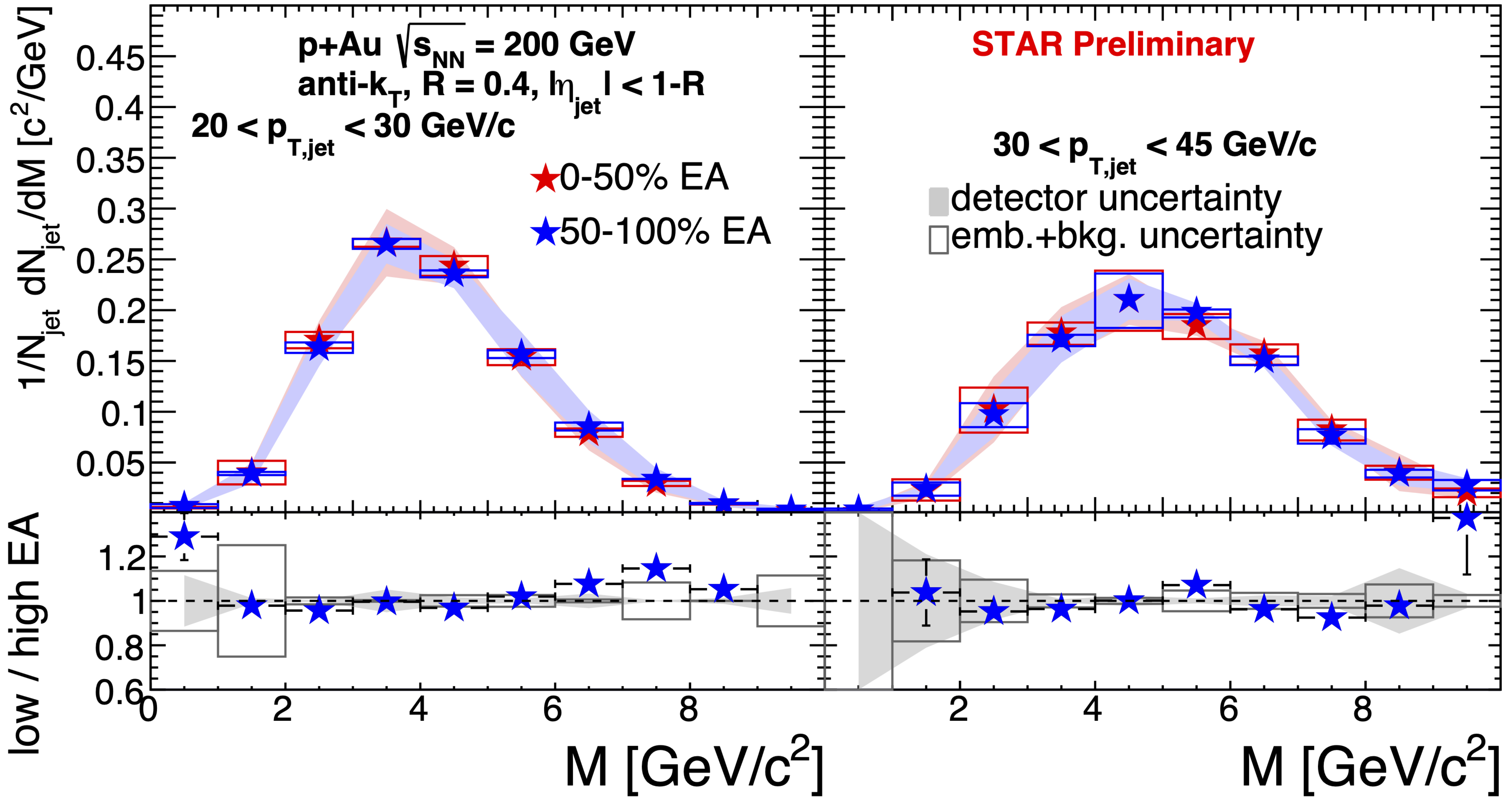




Suppression of yields but not corresponding to typical **surface bias** picture of medium-modification

Interlude: quenching in small systems?

…and by corresponding set of substructure measurements from STAR



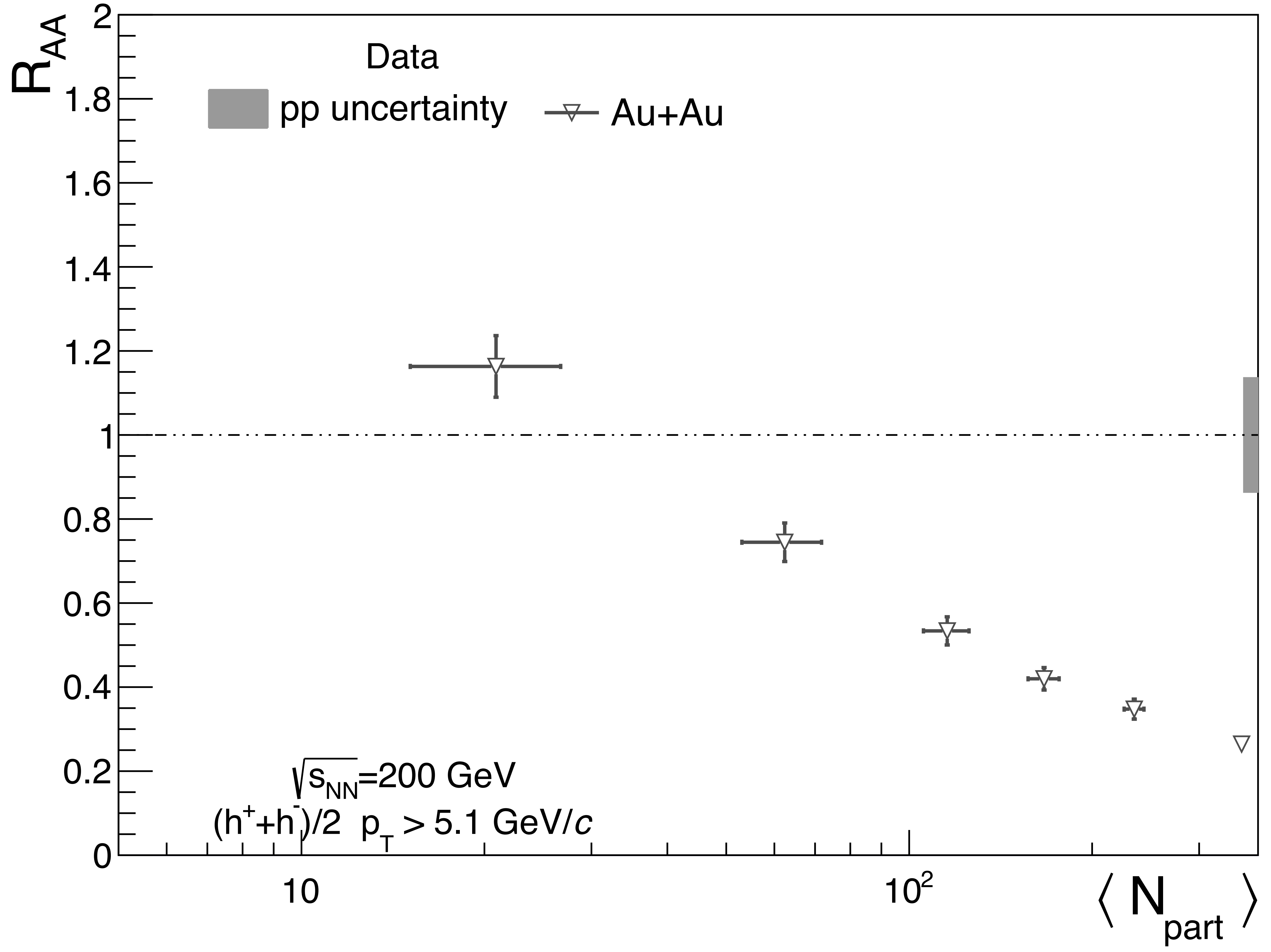
Rather, modifications likely due to **early-time dynamics** and/or **initial state configuration**

Armesto, Gülhan, Milhano, [PLB 747 (2015), 441]

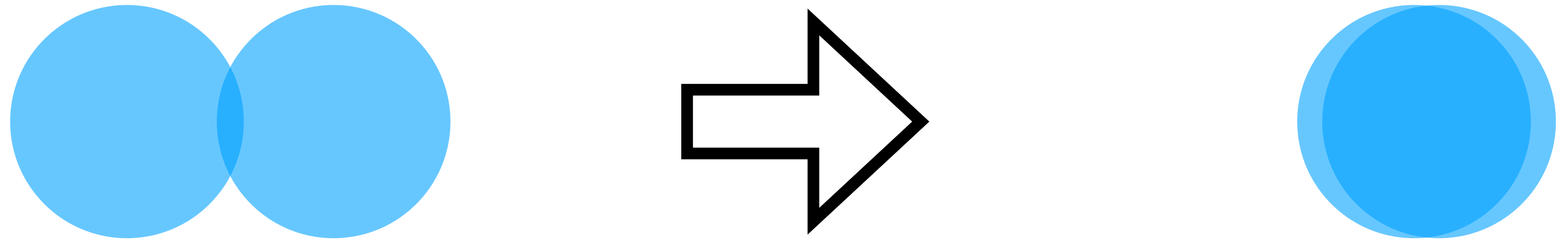
Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, [PRC 93 (2016), 011902(R)]

Inclusive yield modification in heavy-ion collisions

$$R_{AA} = \frac{1}{N_{ev}^{AA}} \frac{d^2N^{AA}/d\eta dp_T}{\langle T_{AA}\rangle\, d^2\sigma^{NN}/d\eta dp_T},\ \langle T_{AA}\rangle = \langle N_{coll}\rangle/\sigma_{inel}^{NN}$$



STAR, PRL 91 (2003), 172302



Suppression of charged hadrons strongly increases with $\langle N_{part}\rangle$

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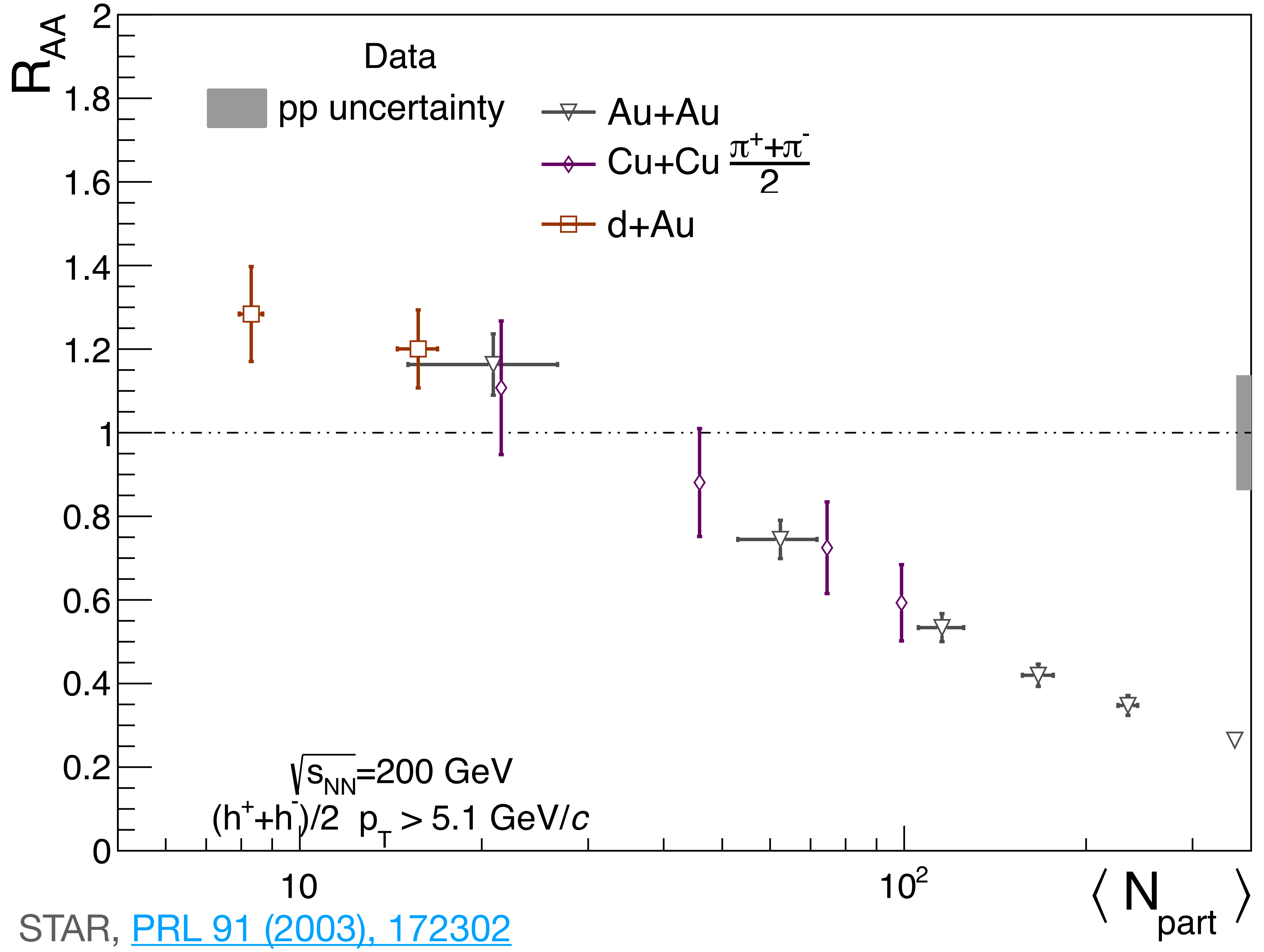
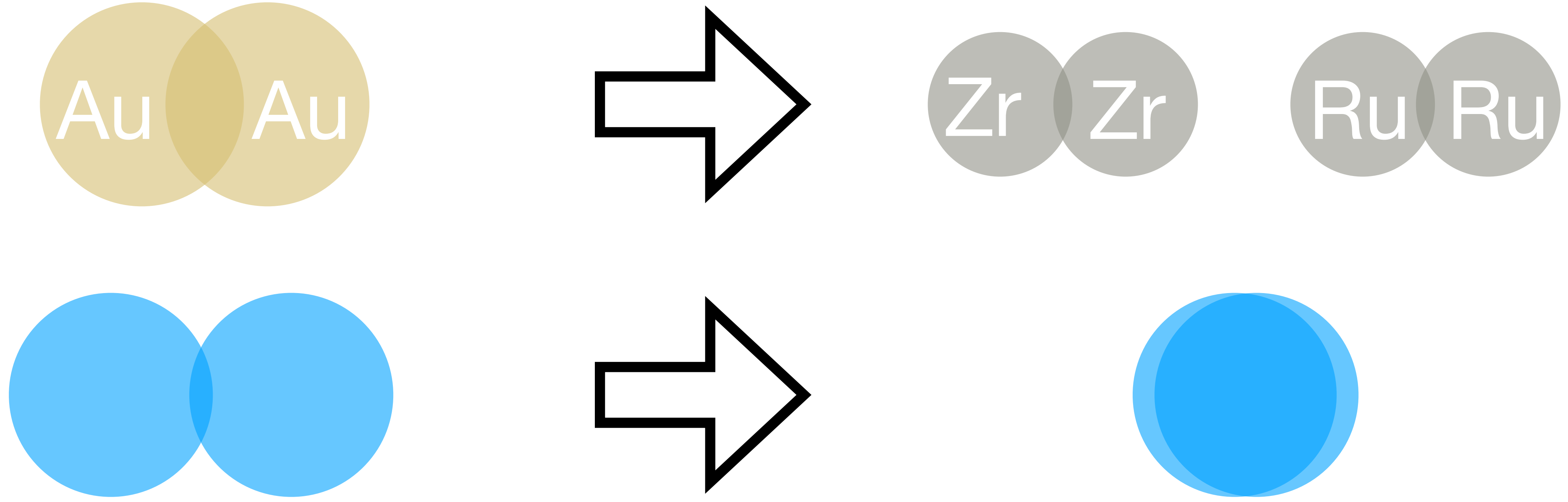


STAR, PRL 91 (2003), 172302
STAR, PRL 91 (2003), 072304
STAR, PRC 81 (2010), 054907



R_{AA} falls with $\langle N_{part} \rangle$ independent of collision species (system size)

Inclusive yield modification in heavy-ion collisions

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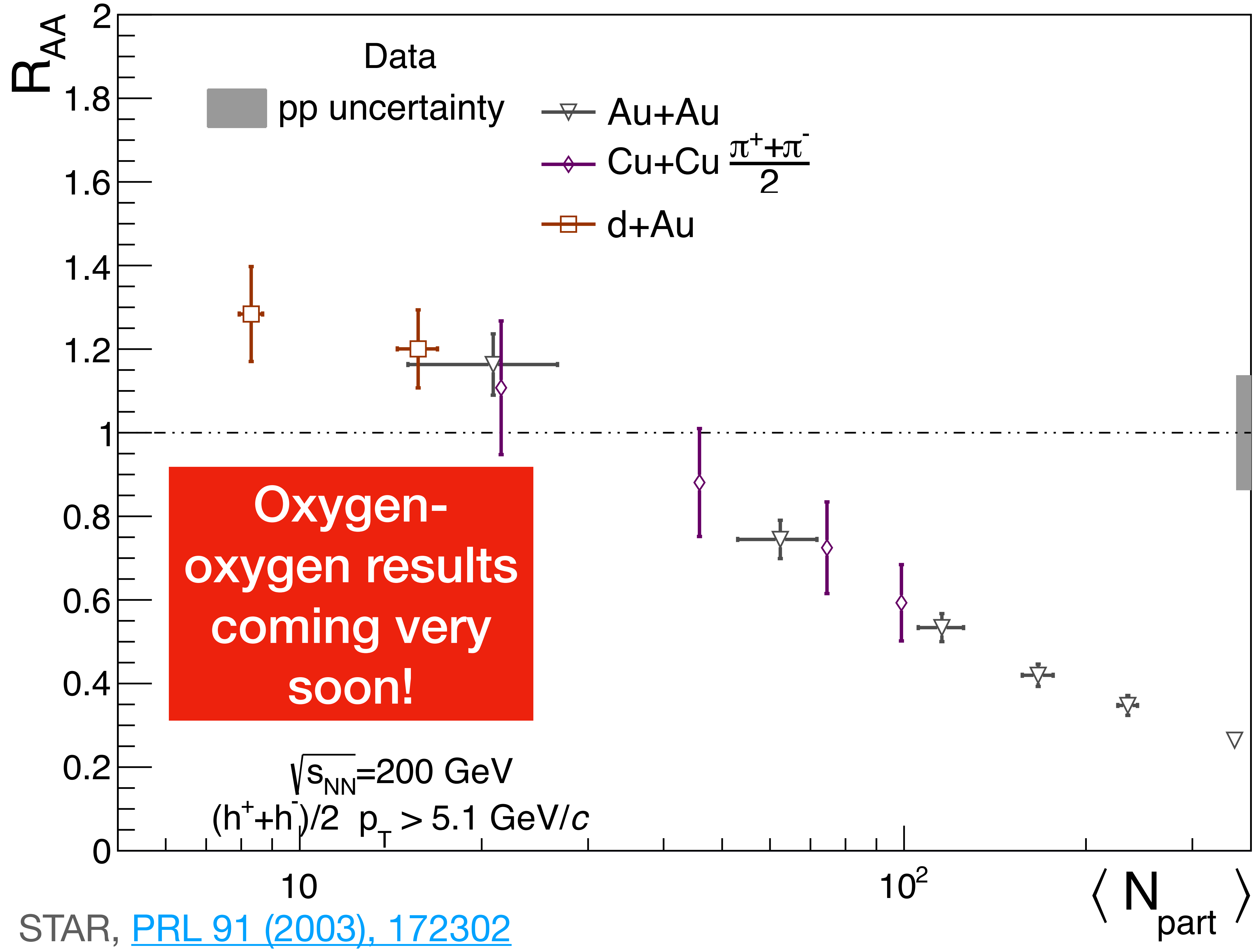

STAR, PRL 91 (2003), 172302
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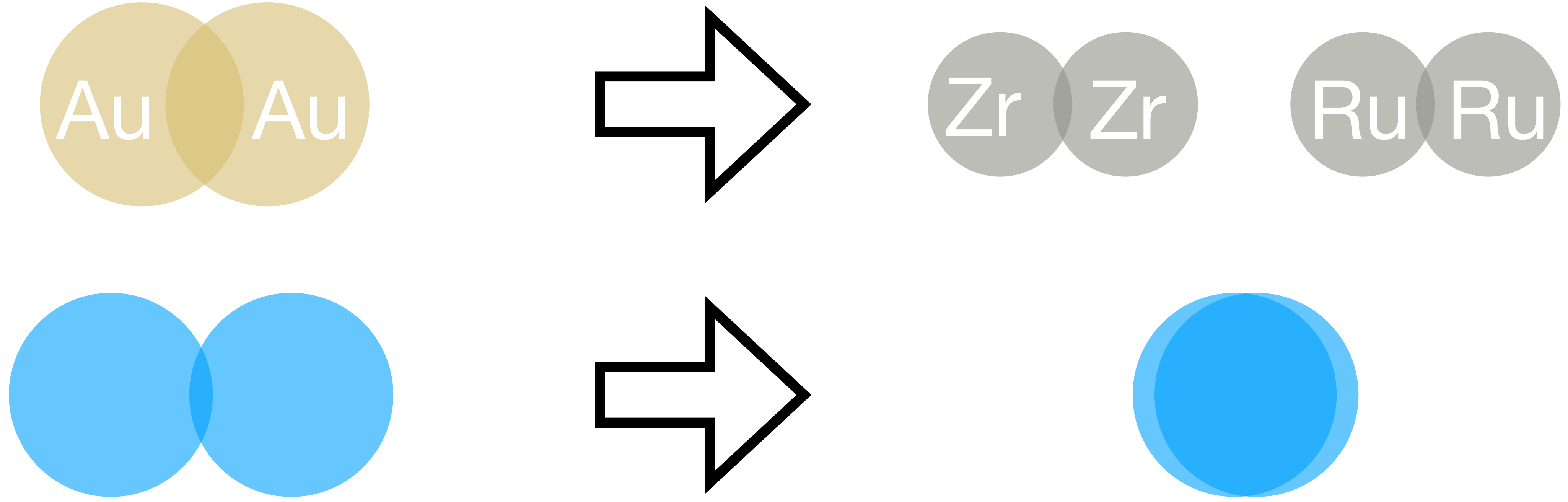

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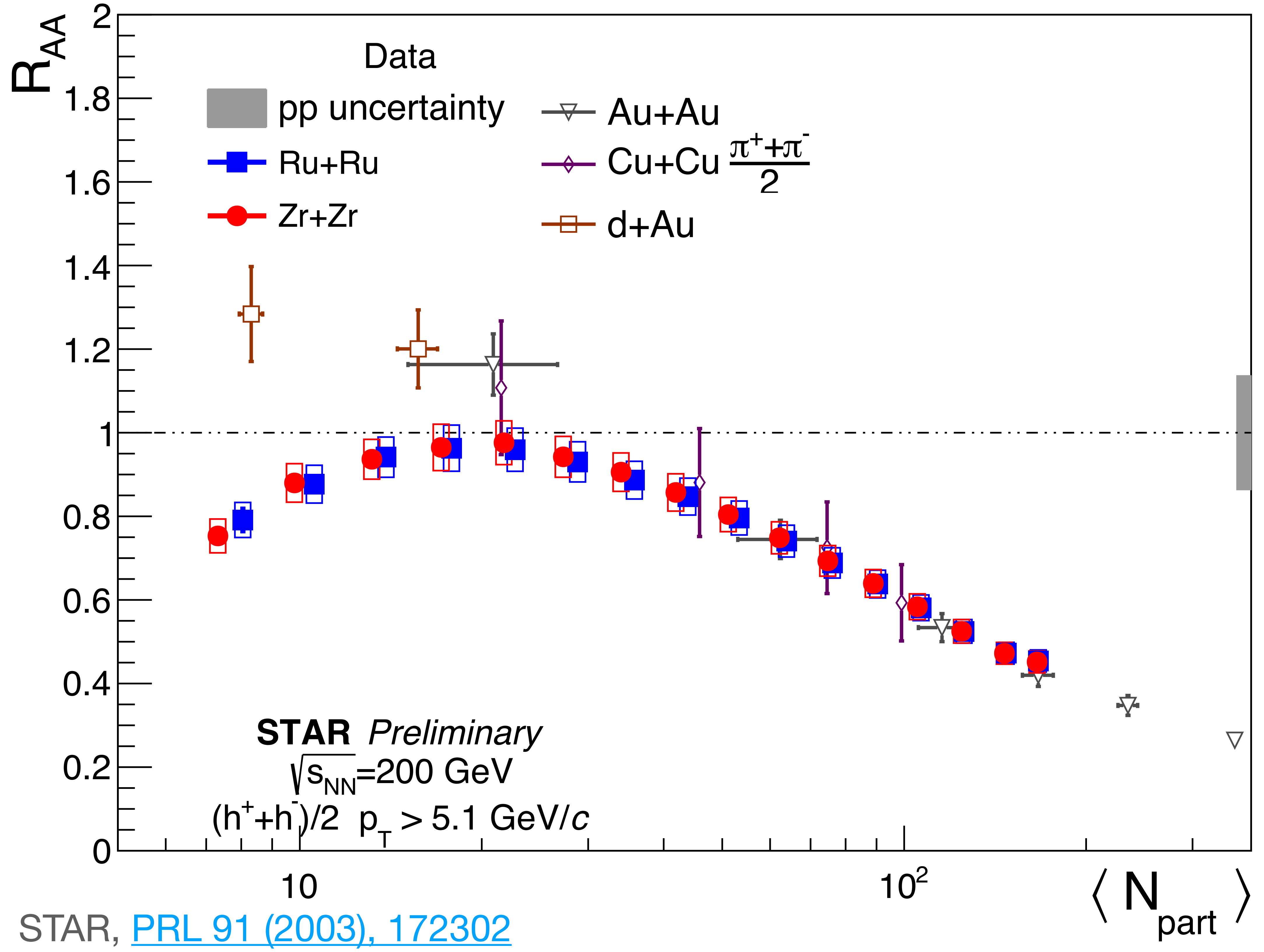

STAR, PRL 91 (2003), 172302
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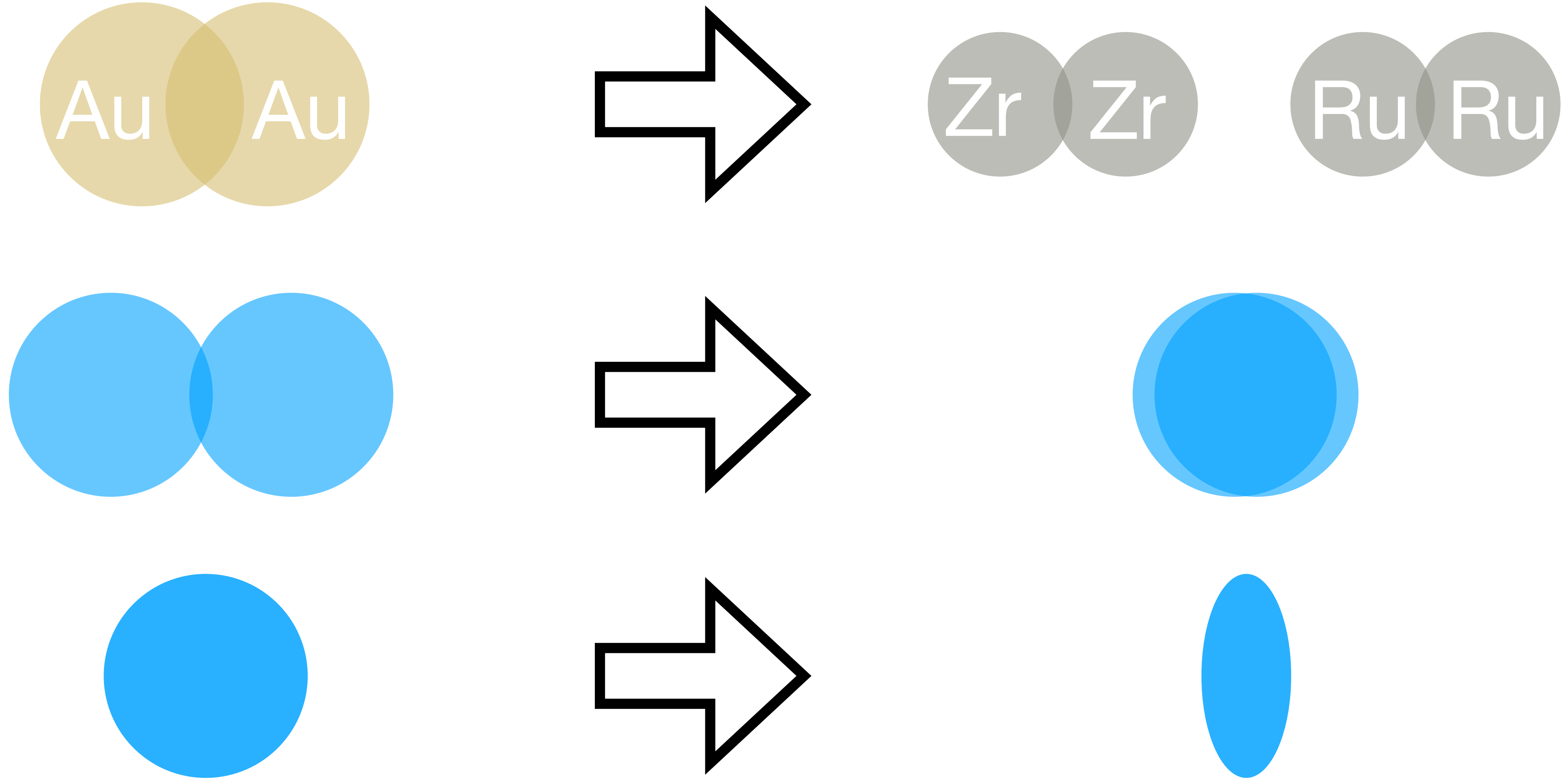
STAR, PRC 81 (2010), 054907



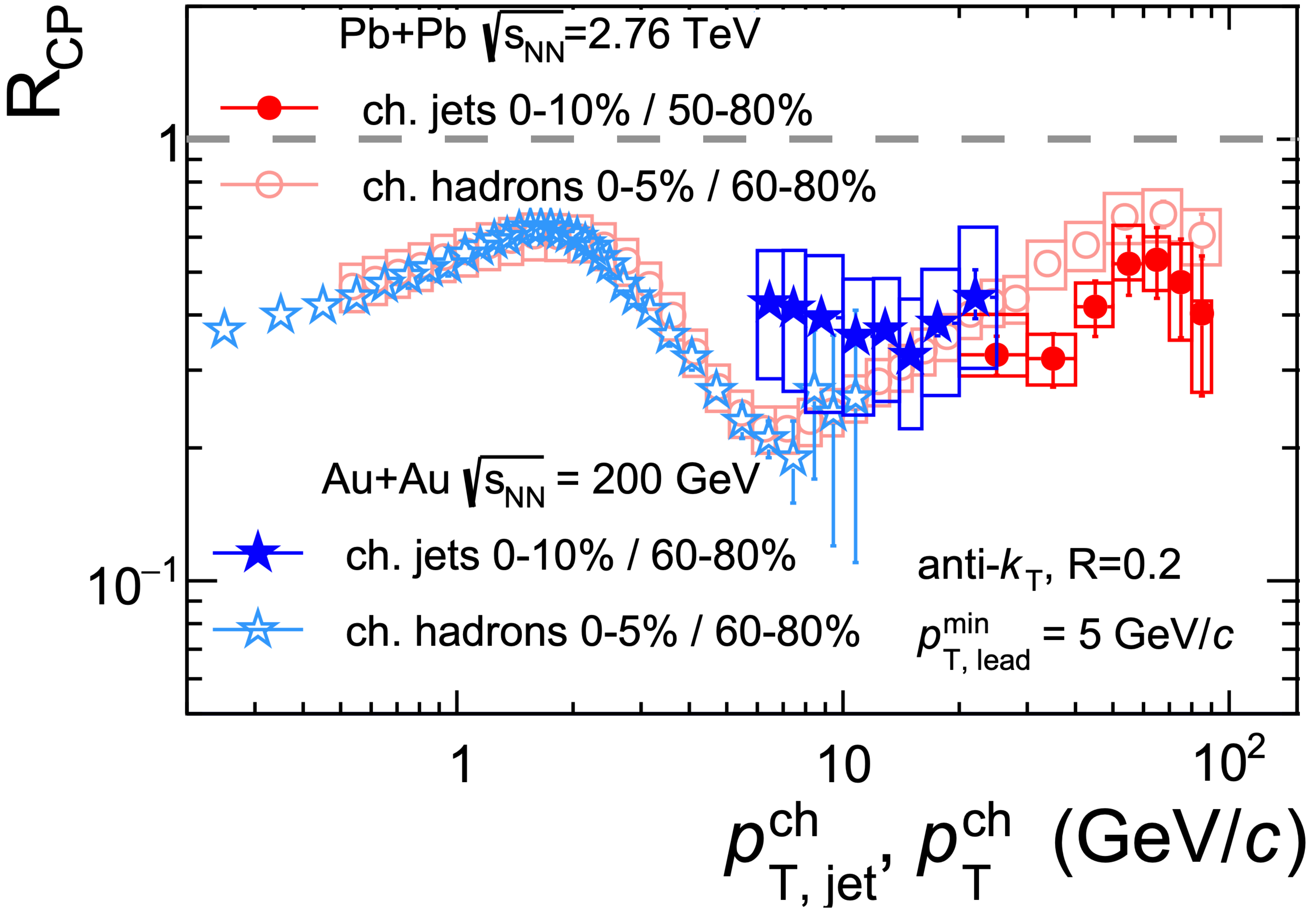
R_{AA} falls with $\langle N_{part}\rangle$ independent of collision species (system size), above ~ 20

Later: for given $\langle N_{part}\rangle$, how does geometry influence E-loss?

Inclusive yield modification of jets

$$R_{\mathrm{CP}} = \frac{N_{\mathrm{ev}}^{\mathrm{P}}}{N_{\mathrm{ev}}^{\mathrm{C}}} \frac{\langle T_{\mathrm{AA,P}} \rangle}{\langle T_{\mathrm{AA,C}} \rangle} \frac{d^2N^{\mathrm{C}}/d\eta dp_{\mathrm{T}}}{d^2N^{\mathrm{P}}/d\eta dp_{\mathrm{T}}}, \langle T_{\mathrm{AA}} \rangle = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

STAR, PRC 102 (2020) 5, 054913, STAR, PRL 91 (2003) 172302, ALICE, JHEP 03 (2014) 013, ALICE, JHEP 09 (2015) 050



Jet R_{AA} consistent with *hadron* R_{AA}

Strong suppression across p_T

RHIC and LHC jets already have kinematic overlap

Similar quenching?

Inclusive yield modification of jets

$$R_{CP} = \frac{N^{P}_{ev}}{N^{C}_{ev}} \frac{\langle T_{AA,P} \rangle}{\langle T_{AA,C} \rangle} \frac{d^2N^{C}/d\eta dp_T}{d^2N^{P}/d\eta dp_T}, \langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma^{NN}_{inel}$$

STAR, PRC 102 (2020) 5, 054913, STAR, PRL 91 (2003) 172302,
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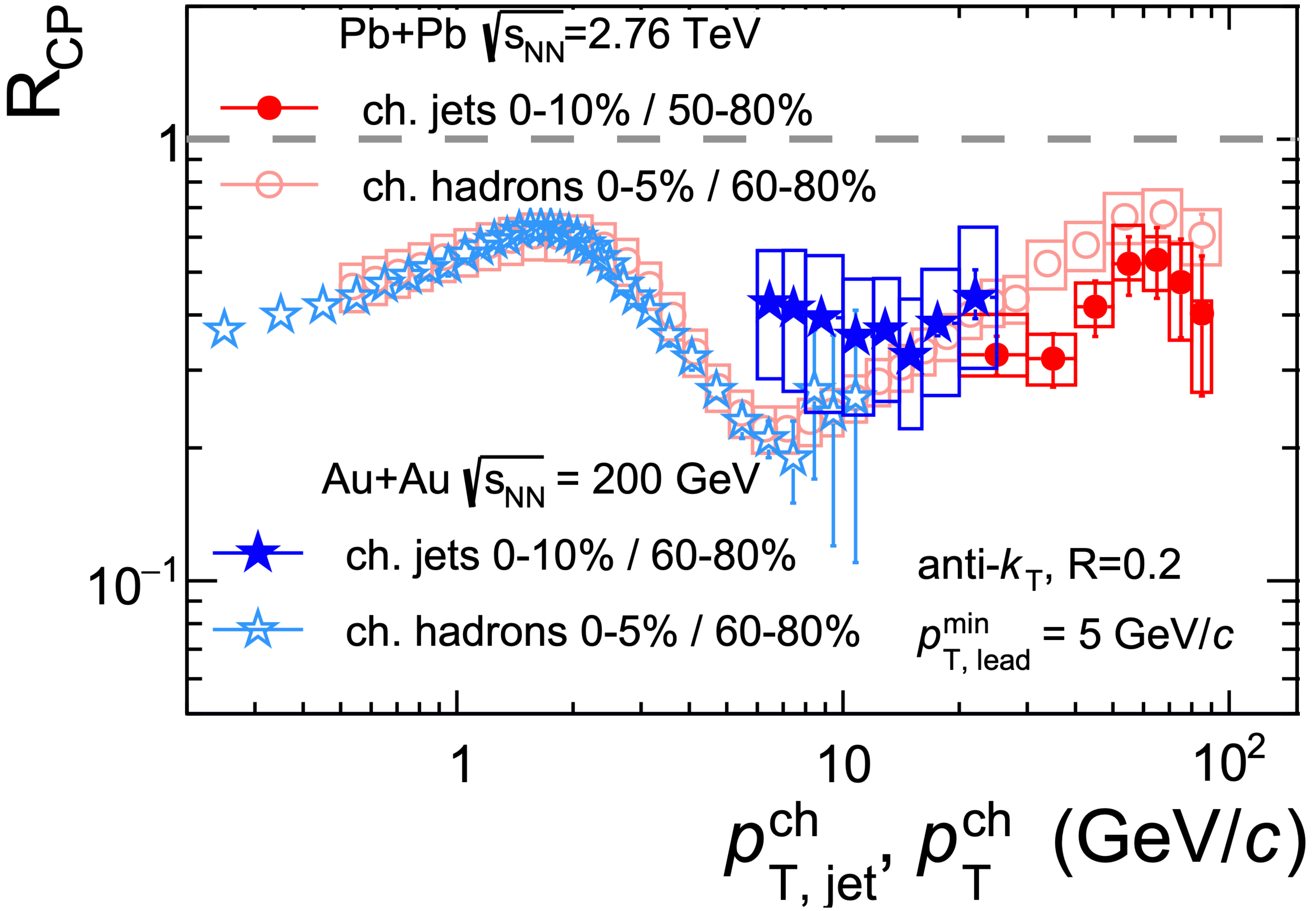


Jet R_{AA} consistent with *hadron* R_{AA}

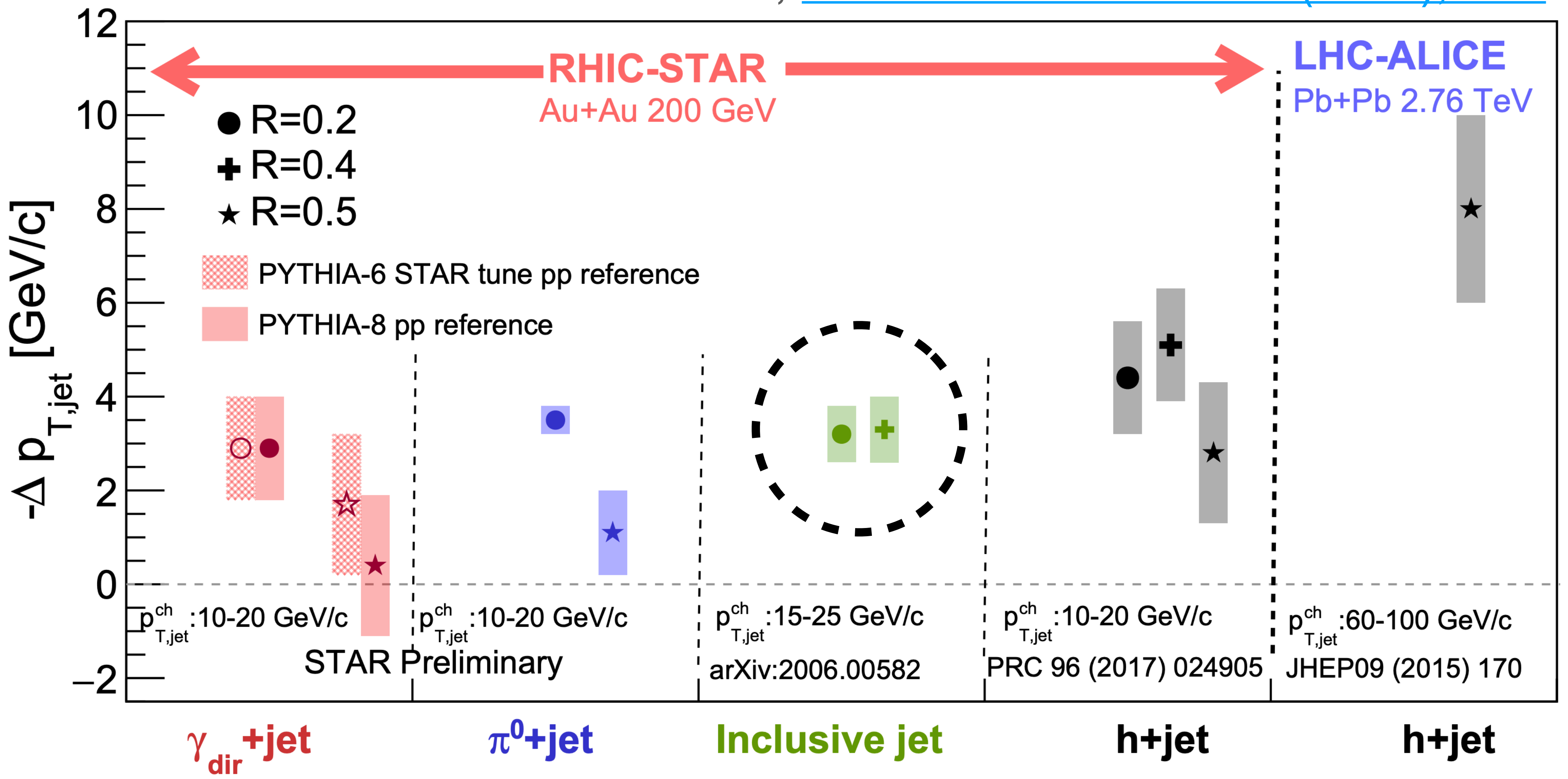
Strong suppression across p_T

RHIC and LHC jets already have kinematic overlap

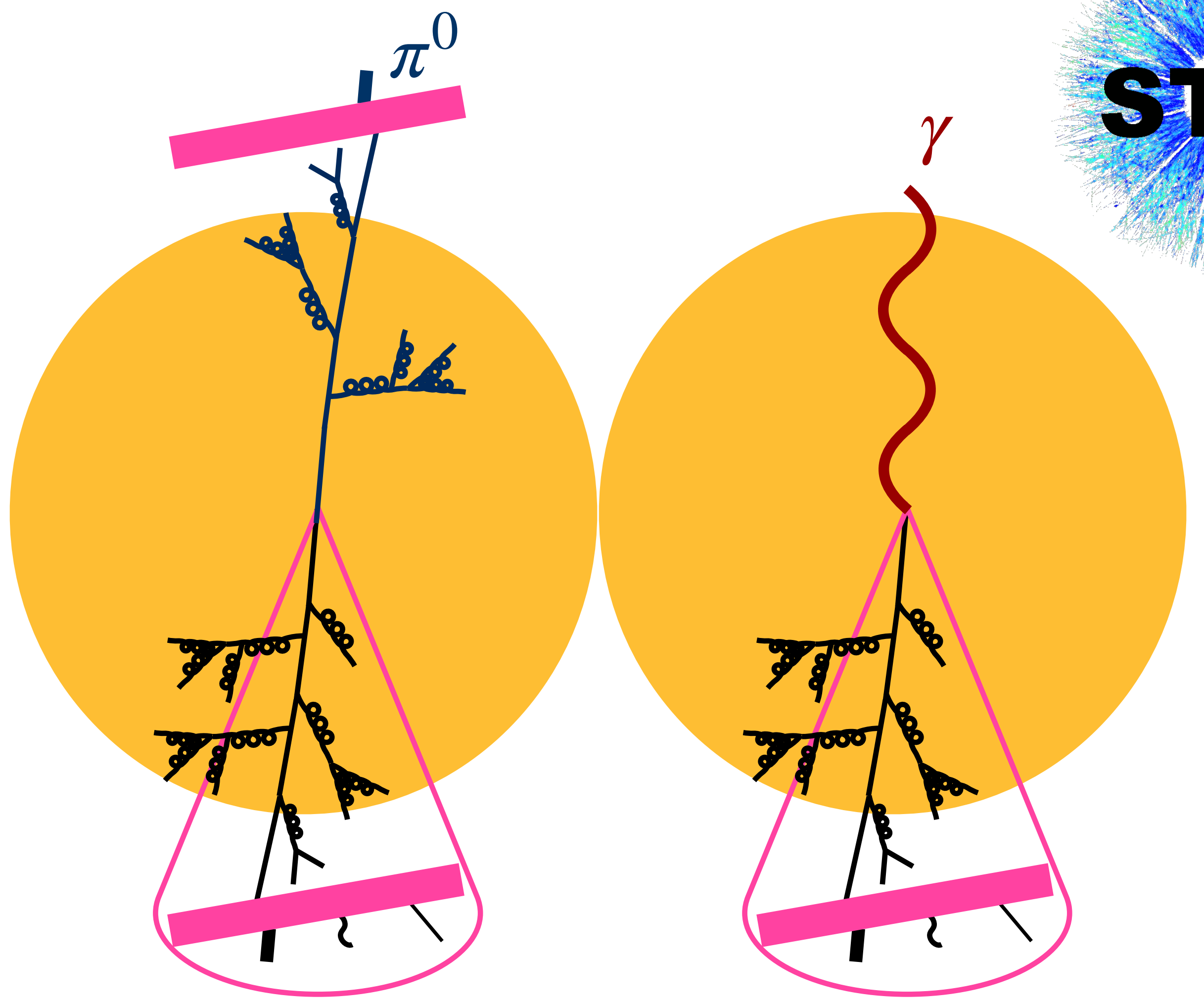
Similar quenching?

Absolute, smaller. Relative, *larger!*

Sahoo, PoS HardProbes2020 (2021), 132

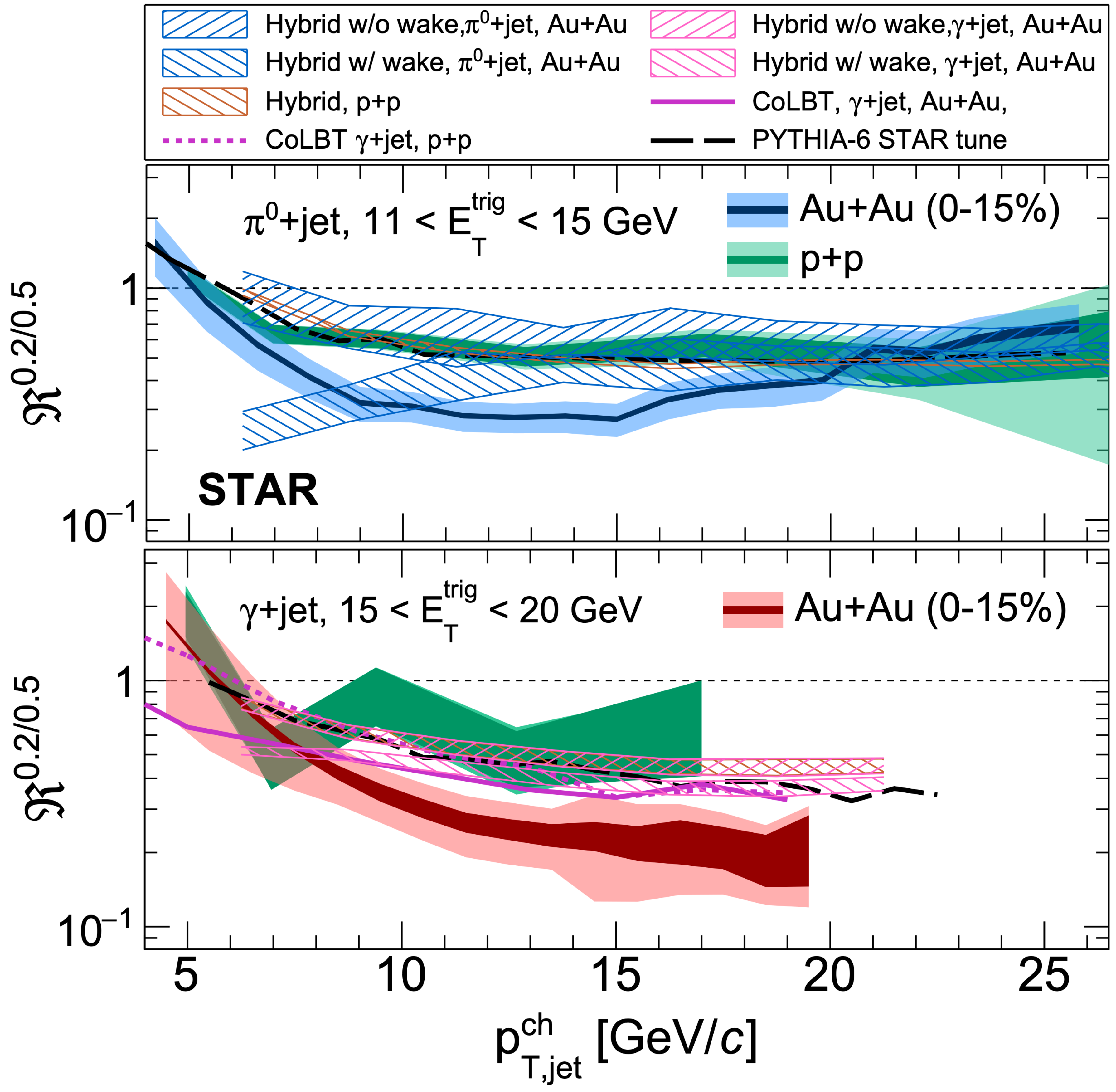


Semi-inclusive yield modification



$$I_{AA} = \frac{Y^{AA}(p^{ch}_{T,jet}, R)}{Y^{pp}(p^{ch}_{T,jet}, R)}, \; Y(p^{ch}_{T,jet}, R) = \frac{1}{N_{trig}} \int_{3\pi/4}^{5\pi/4} d\Delta\phi \left[\frac{d^2 N_{jet}(R)}{dp^{ch}_{T,jet} d\Delta\phi} \right]_{E_T^{trig} \in [E_T^{min}, E_T^{max}]}$$

STAR, arXiv:2309.00145, STAR, arXiv:2309.00156

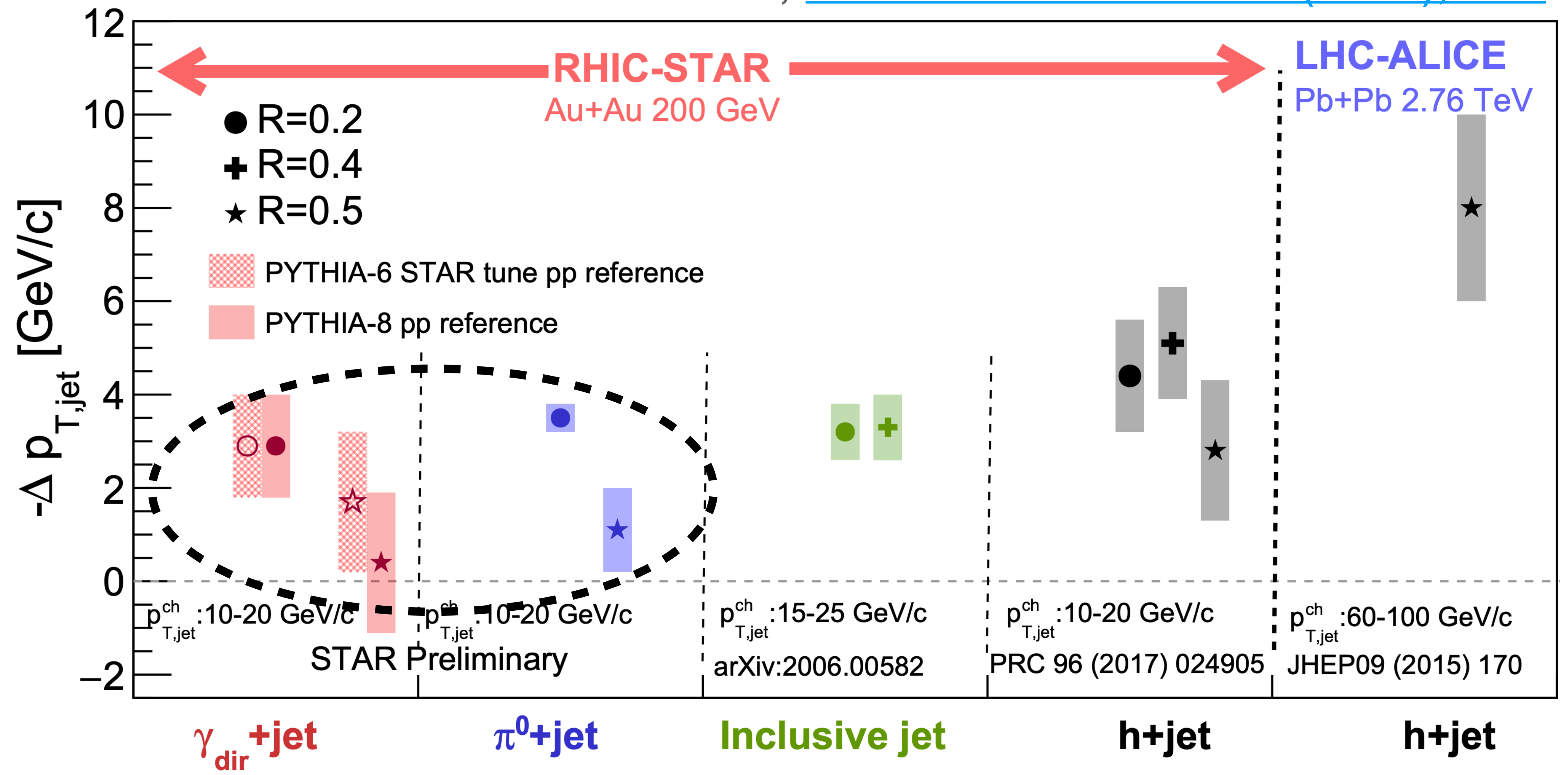


Recoil jet yield suppression in Au+Au, stronger in small R jets

Clear observation of *intra-jet broadening*

Models unable to quantitatively describe the effect

Sahoo, PoS HardProbes2020 (2021), 132



Path-length-dependent quenching

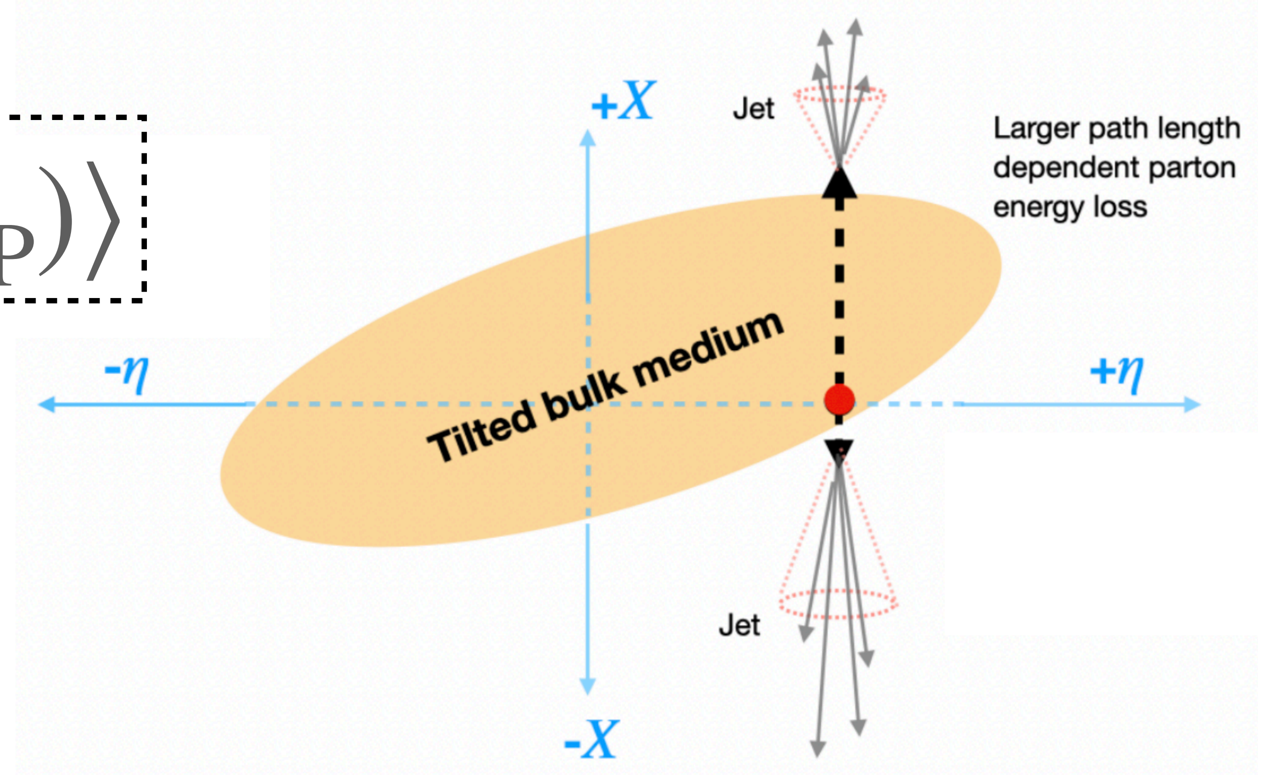
Bulk is tilted in heavy-ion collisions[1,2] causing asymmetric paths for isotropically produced hard probes

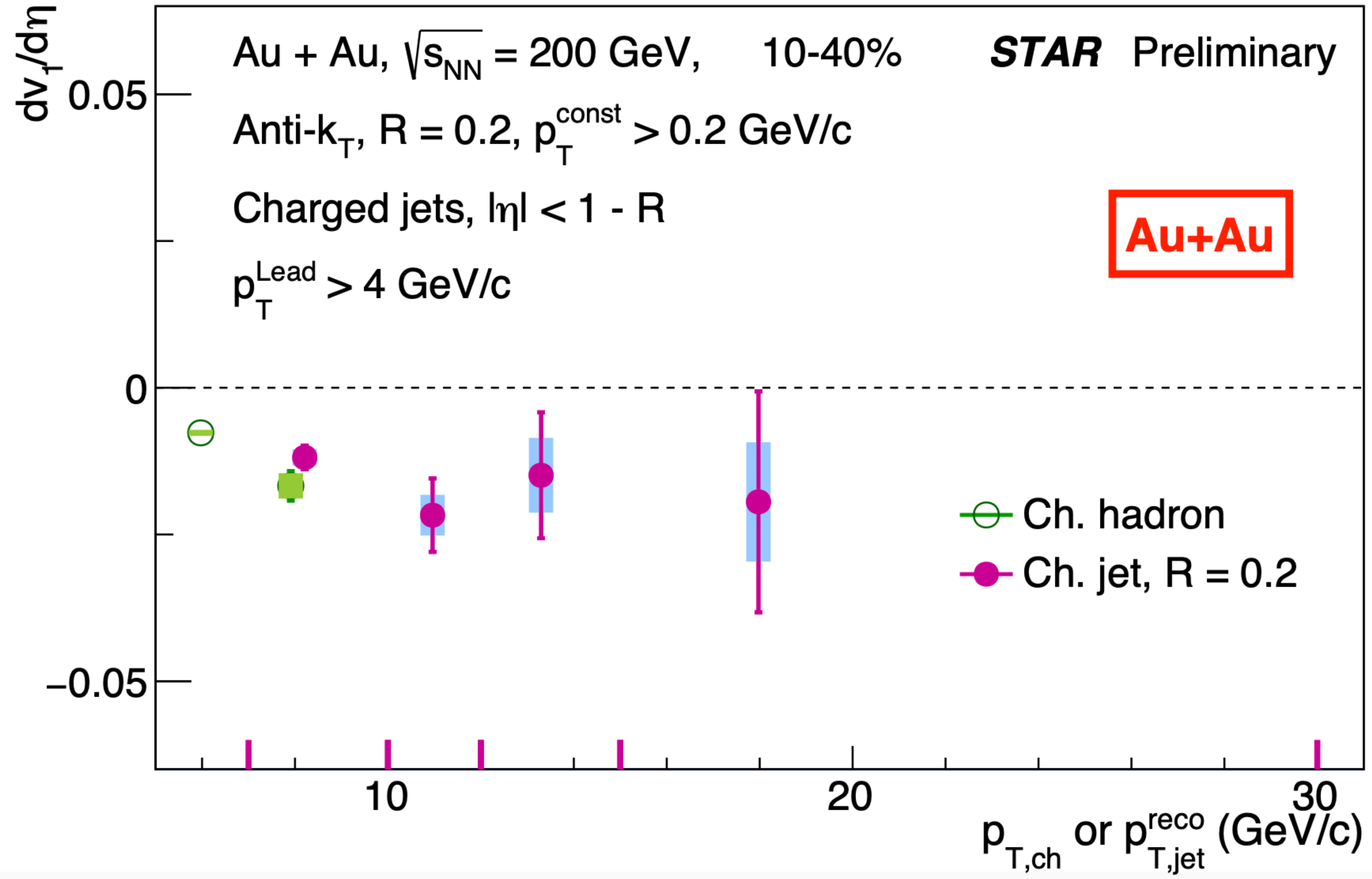
Jet v_1: a new observable to probe *pathlength-dependent energy loss* in QGP

Clear v_1 **signal** for all studied jet R, p_T : $7-20$ GeV/c, in **Au+Au** data, similar for **isobar** systems as well

<u>Outlook</u>: event-shape engineering with multiplicity fluctuations

$$v_1(p_T, y) = \langle \cos(\phi - \Psi_{RP}) \rangle$$





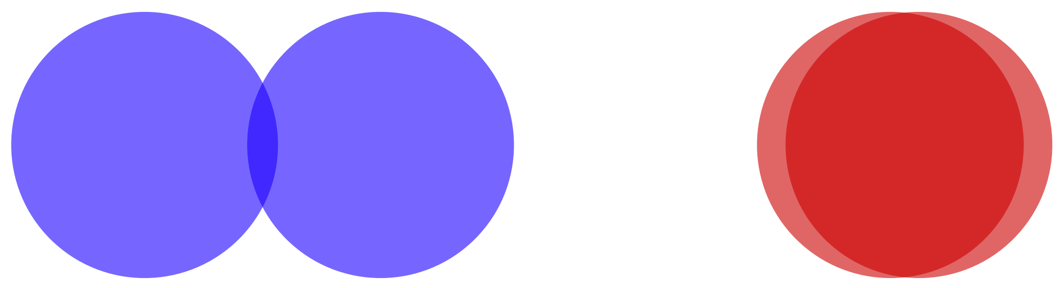
[1]Chatterjee, Bożek, PRL 120 (2018) 19, 192301
[2]STAR, PRL 123 (2019) 16, 162301

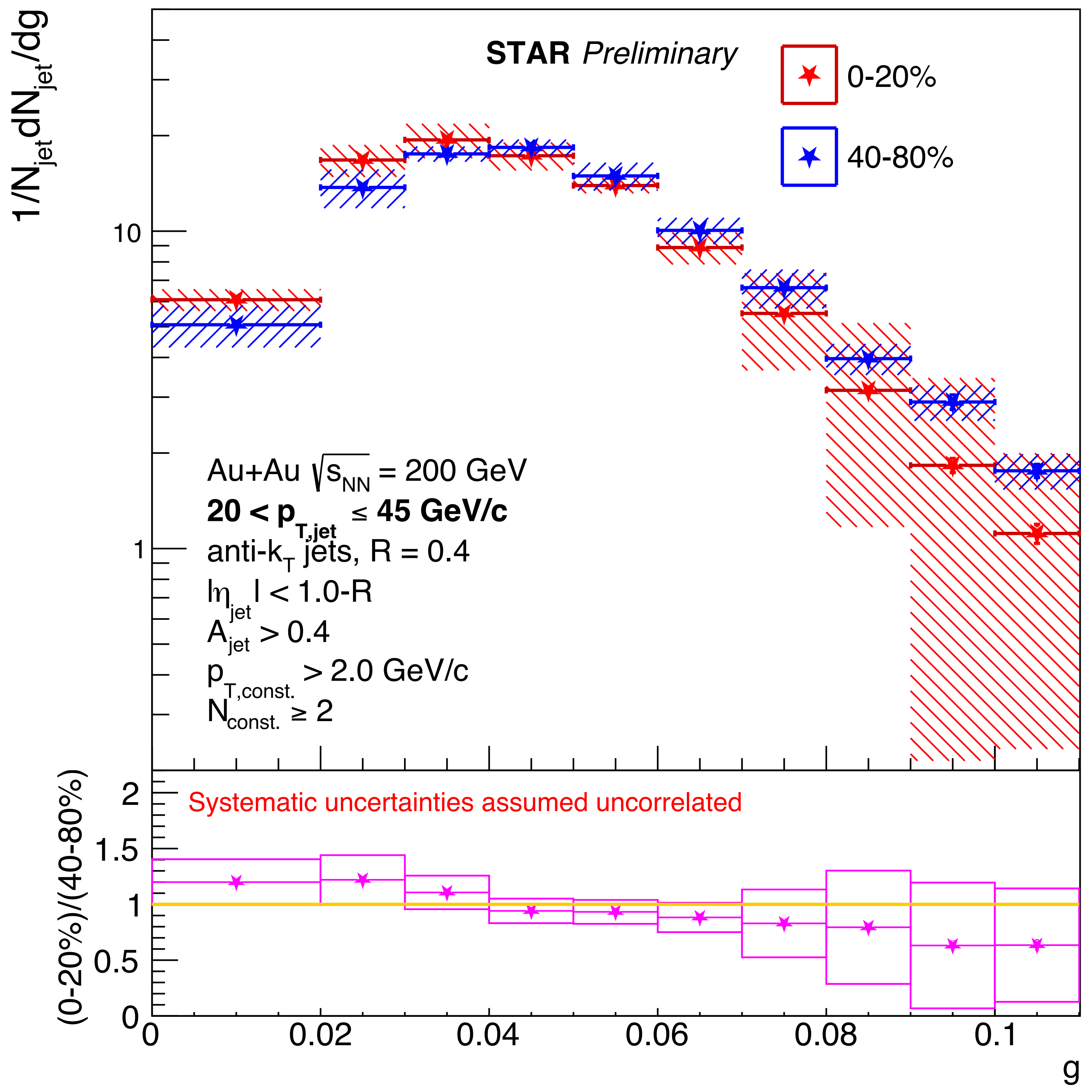
Generalized angularities

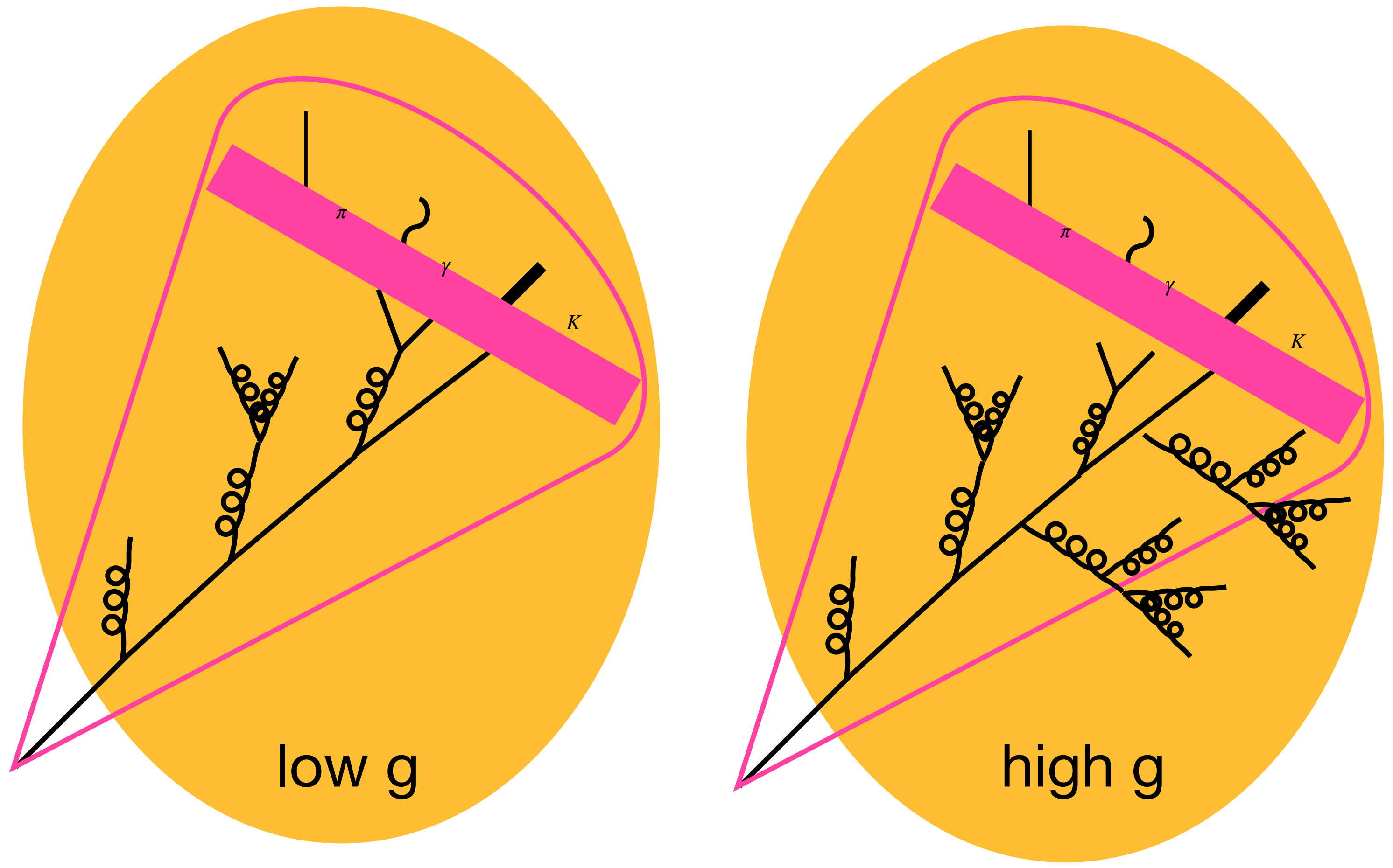
With MultiFold

$$\lambda_\beta^\kappa = \sum_{\mathrm{cons}\in\mathrm{jet}} \left(\frac{p_{\mathrm{T,cons}}}{p_{\mathrm{T,jet}}}\right)^\kappa \Delta R\,(\mathrm{cons,jet})^\beta$$

$$g = \lambda_1^1 = \frac{\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T,trk}} \Delta R}{p_{\mathrm{T,jet}}}$$







Data corrected using MultiFold in 7D

Generalized angularities allow tunable contribution of momentum, angular scales in IRC safe way

With conservative systematic uncertainties *in biased pop.*, girth in peripheral and central collisions are consistent

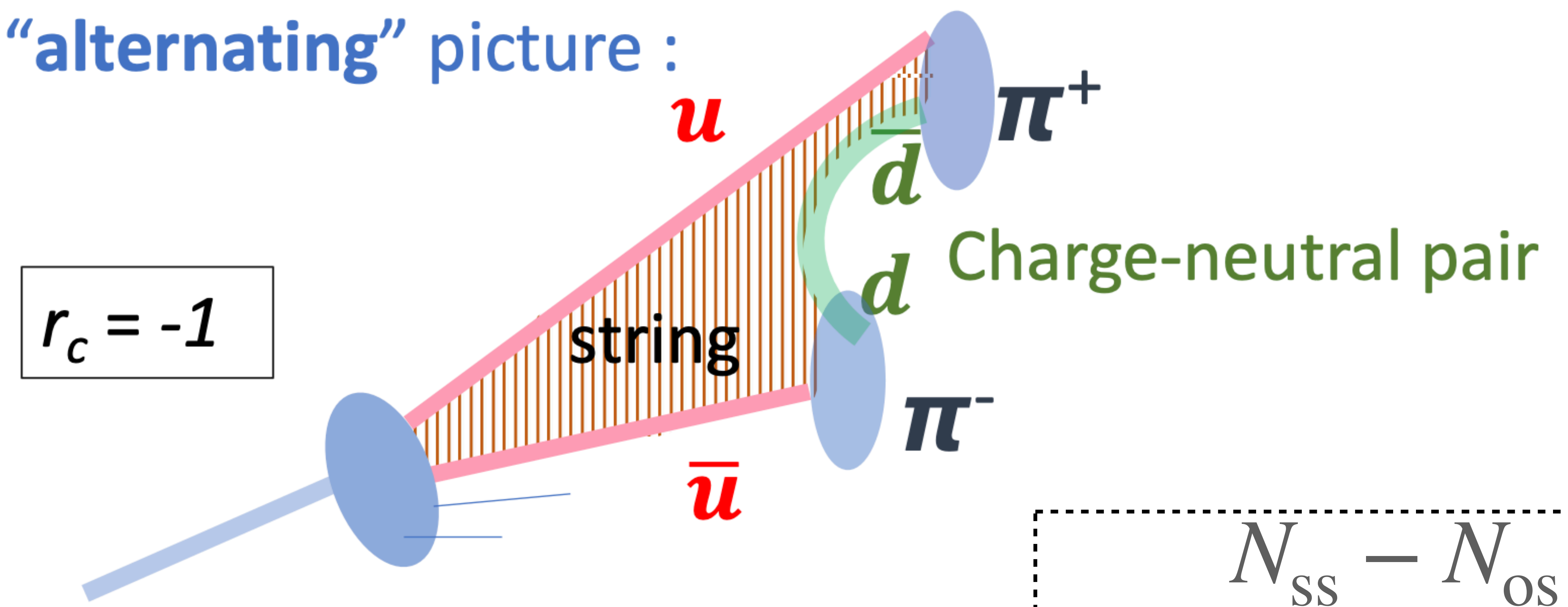
Charm quark energy loss, diffusion, fragmentation modification in medium with *charmed-jet yields*

Hadronization mechanism with *flavor correlators*

Constituent identity

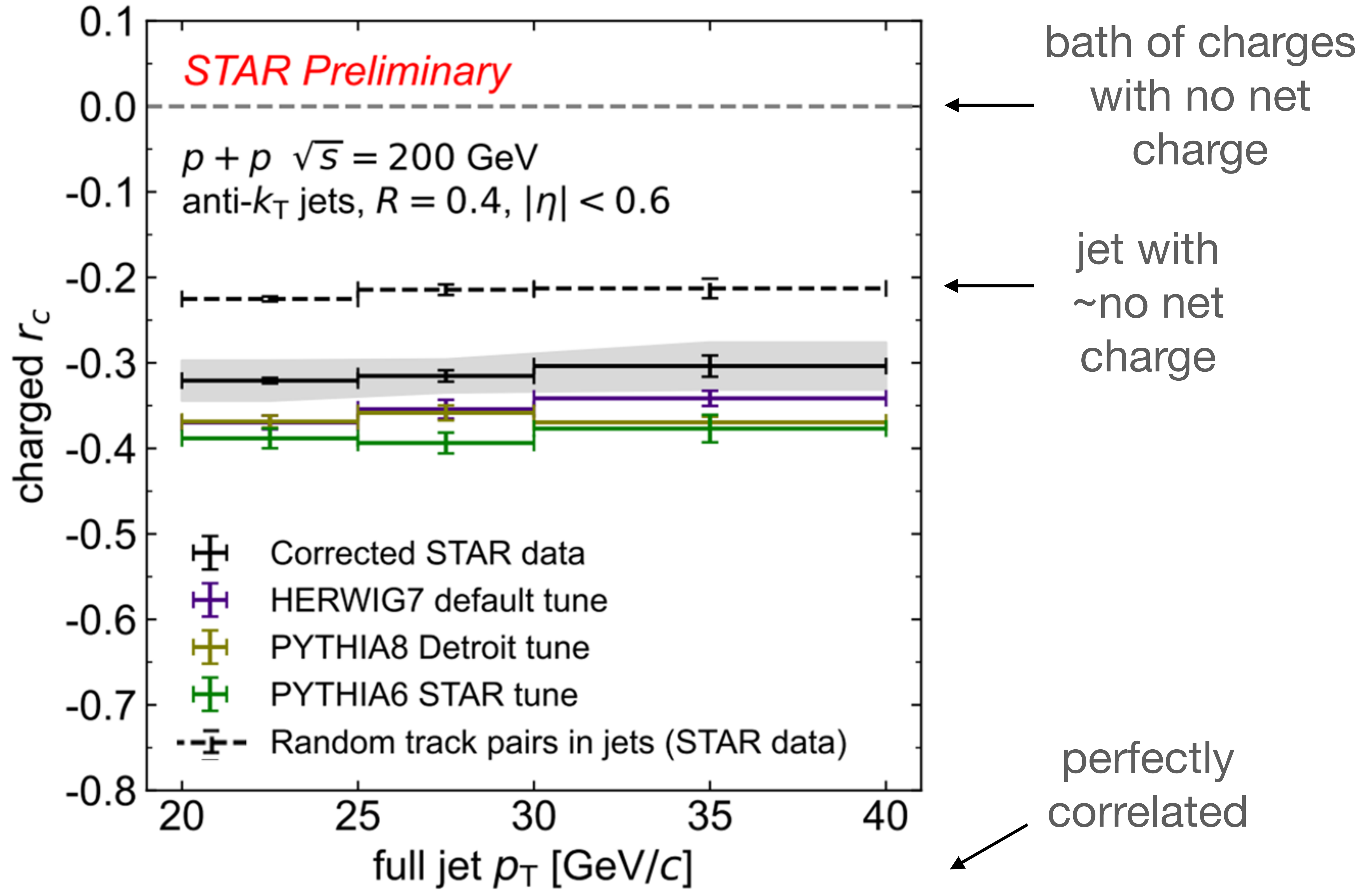
Hadrochemistry modification via medium response with *baryon-to-meson ratios*

Assessing fragmentation mechanism in jets



$$r_c = \frac{N_{SS} - N_{OS}}{N_{SS} + N_{OS}}$$

Leading charge correlator, r_c, can probe contribution of string-like fragmentation

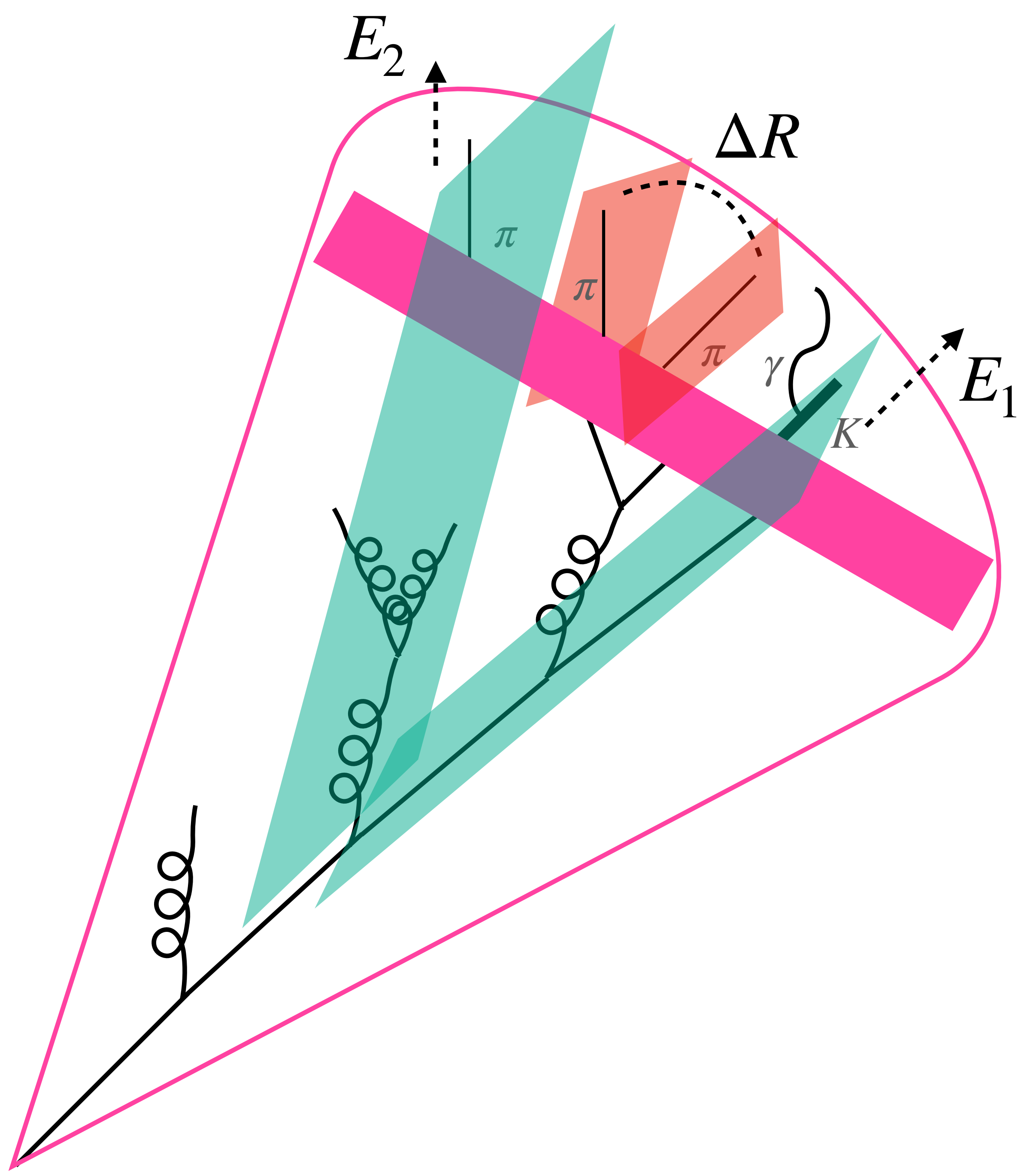


First pp measurement: **MCs predict more charge correlation than supported by data**

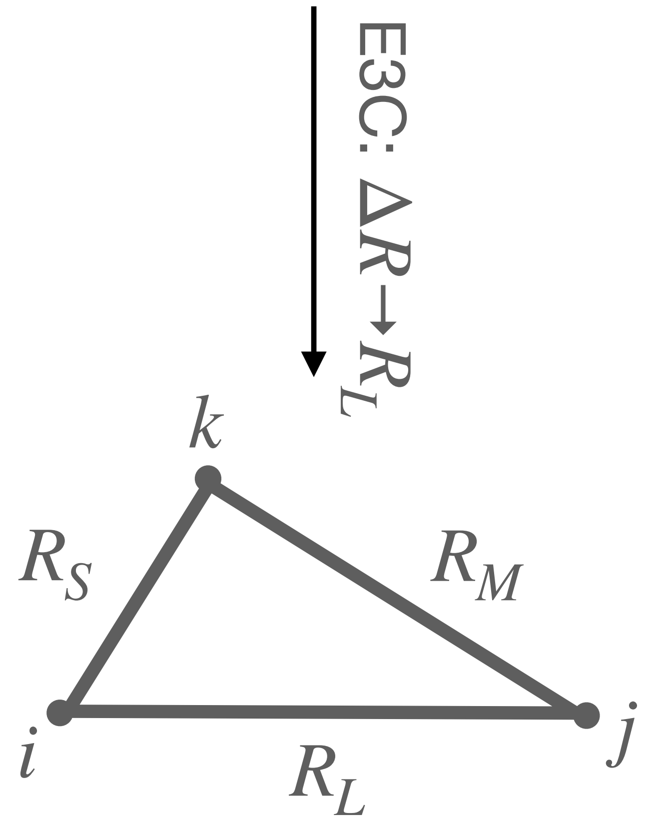
<u>Outlook</u>: extension to heavy-ion collisions ongoing

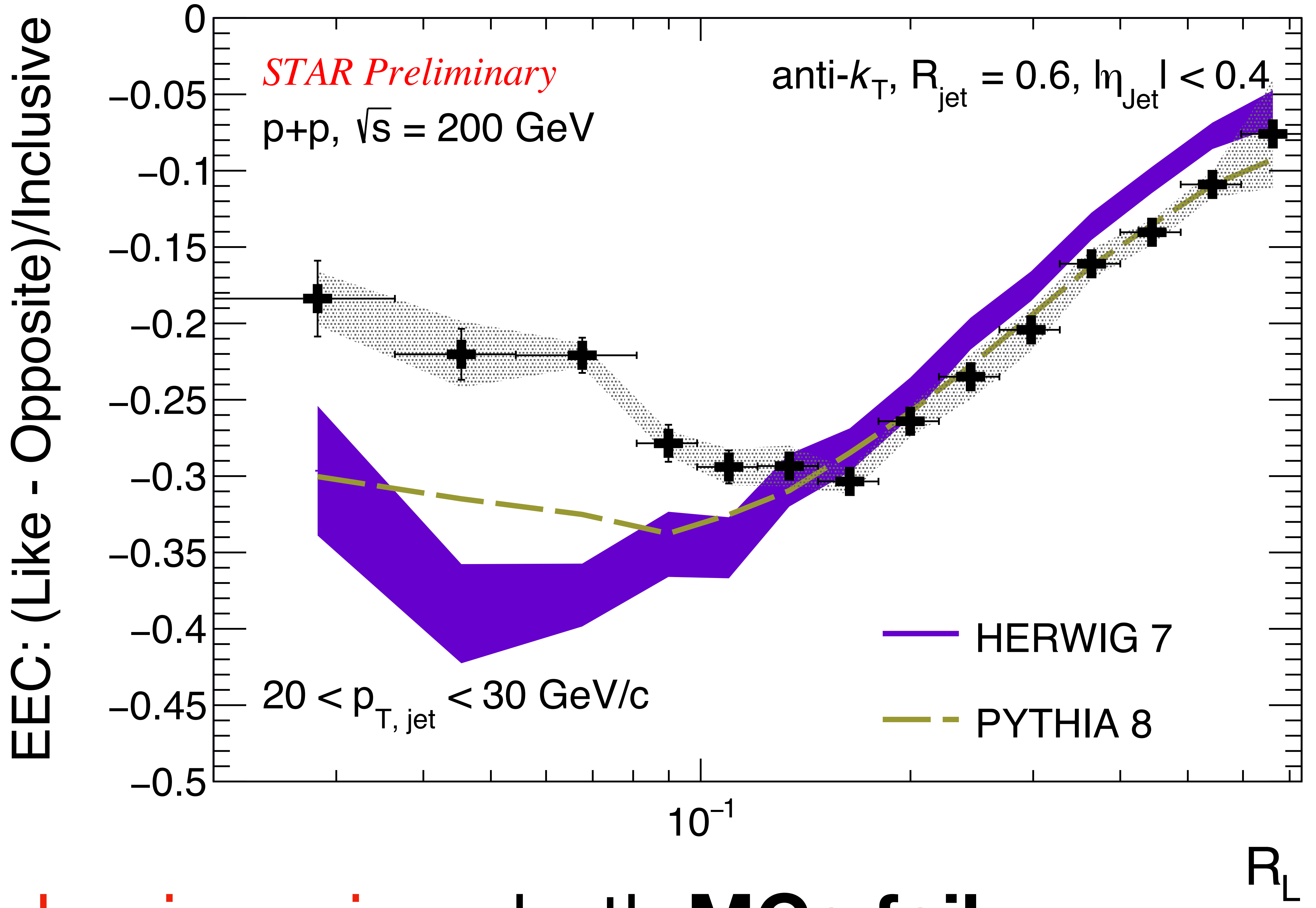
Chien, Deshpande, Mondal, Sterman, PRD 105 (2022) 5, L051502

Assessing fragmentation mechanism in jets



$$\mathrm{EEC}(\Delta R) = \frac{1}{\mathcal{O}} \frac{d\mathcal{O}}{d(\Delta R)},\ \mathcal{O} = \sum_{\text{jets}} \sum_{i \neq j} \frac{E_i E_j}{p^2_{\mathrm{T,jet}}}$$



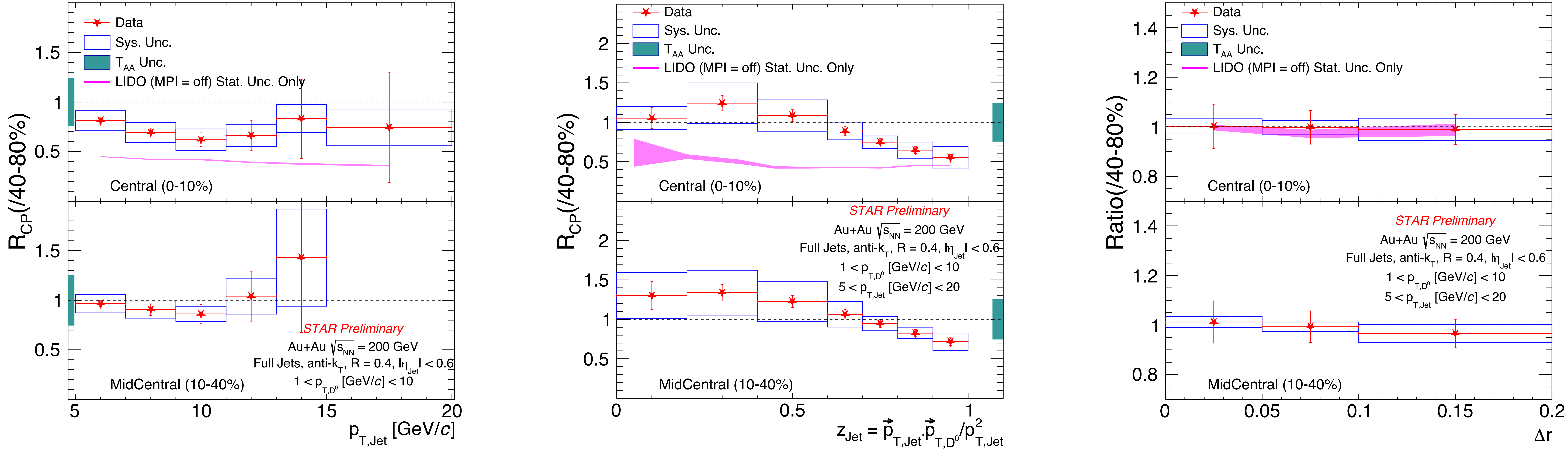


New charge-dependent EEC & E3C — in hadronic regime, both **MCs fail to capture data**; qualitatively consistent with behavior seen in r_c

Outlook: Extension to heavy-ion collisions ongoing

D^0-jet spectra, profile, fragmentation

$D^0 = c\bar{u}$



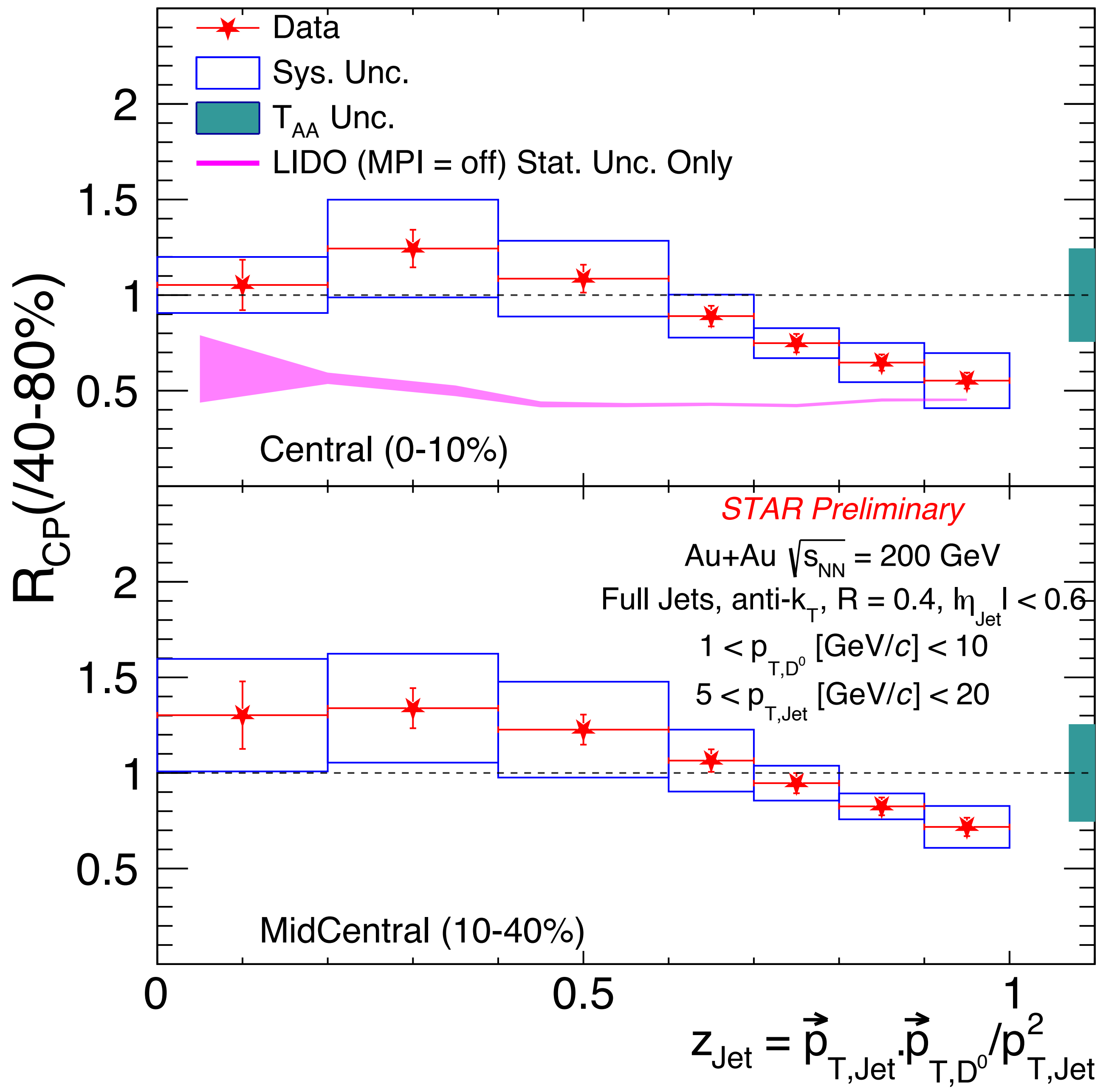
Testing charm quark energy loss, diffusion, and fragmentation modification

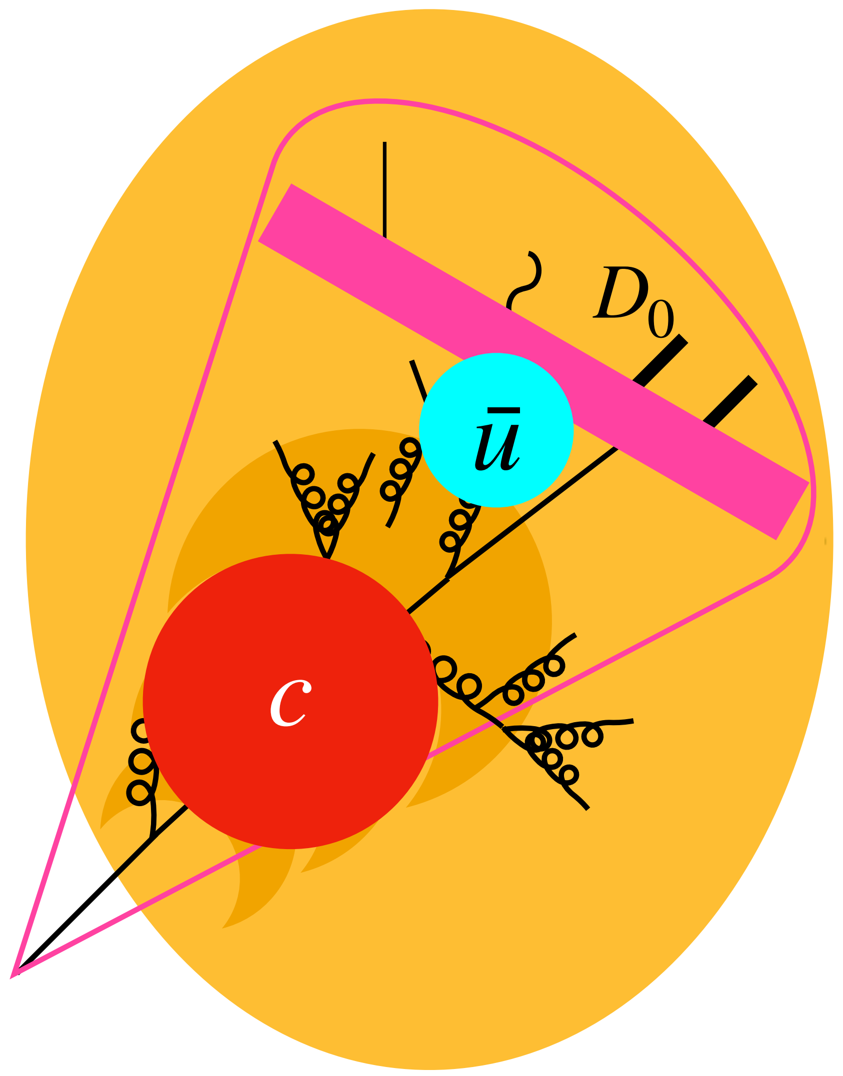
Hint of yield suppression in central. Hard-fragmented charm jets suppressed. *No diffusion.*

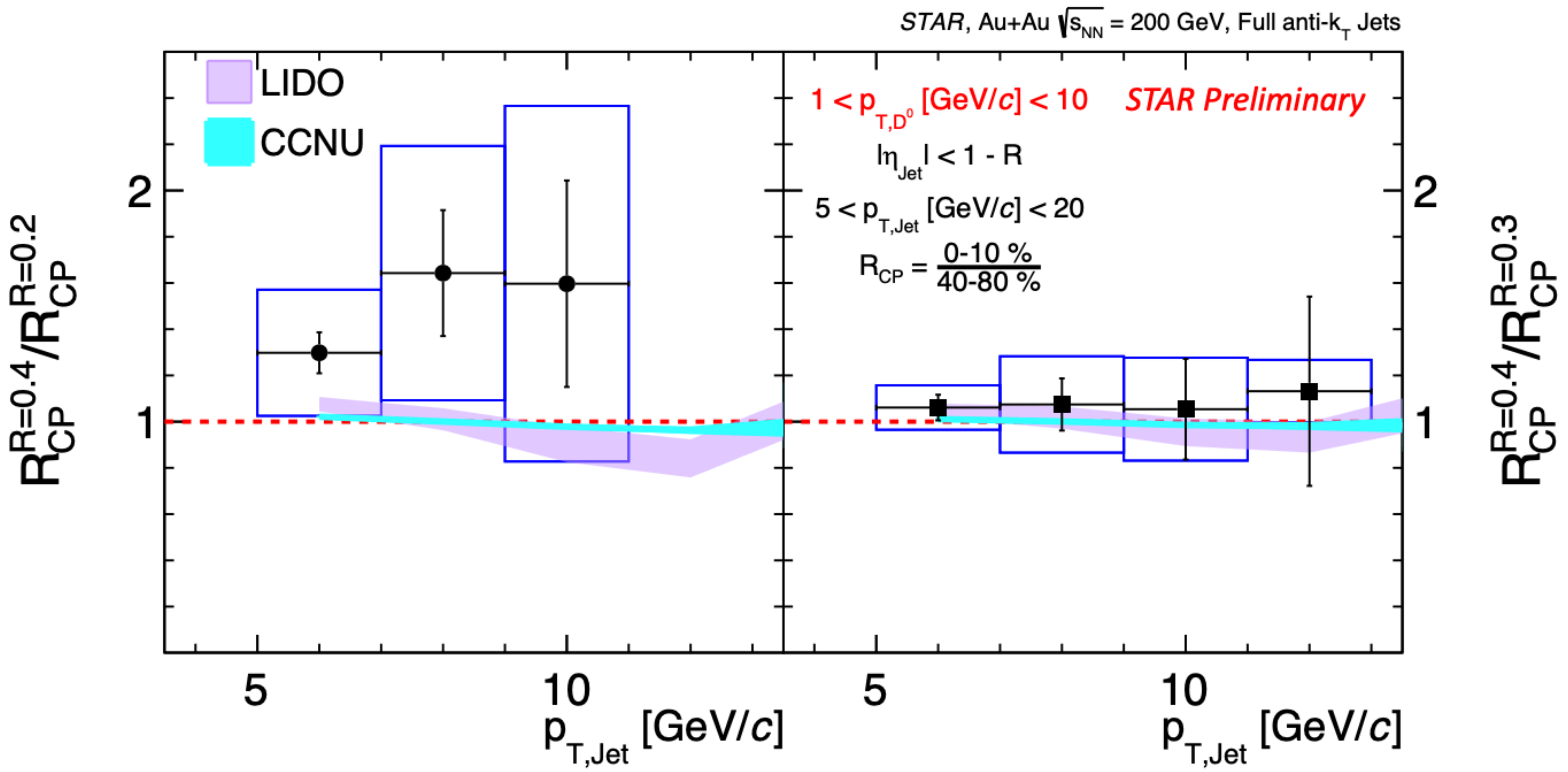
Model including radiative and collisional energy loss during heavy quark evolution underpredicts central yields — MPI might be important for D^0 p_T this low

Ke, Xu, Bass, [PRC 98 (2018) 6, 064901]

Recovering charm-associated radiation







Wider jets → more medium interaction/E-loss $\Longrightarrow$ *ratio* < *1*,

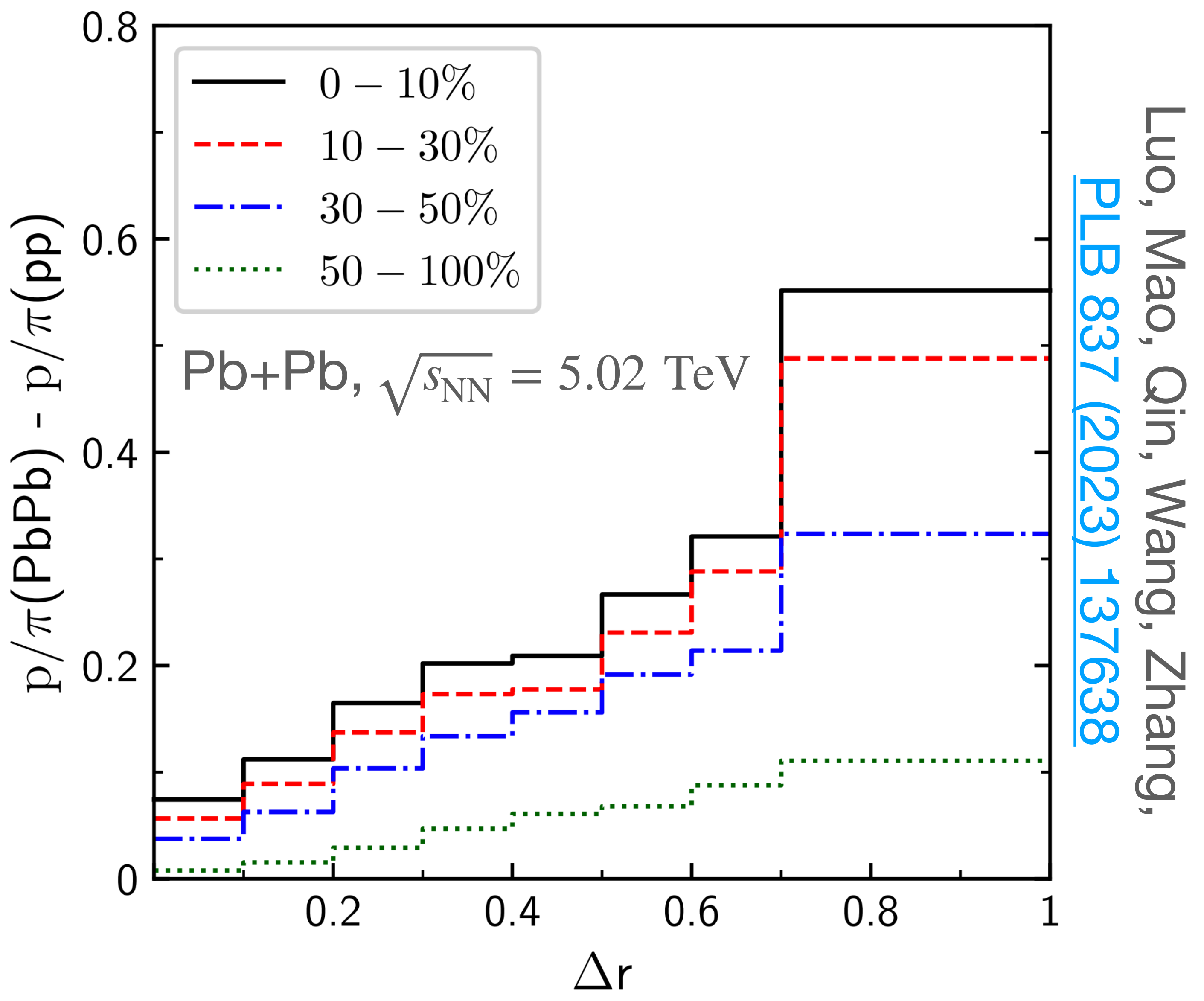
but recover more energy + more potential for medium response $\Longrightarrow$ *ratio* > *1*

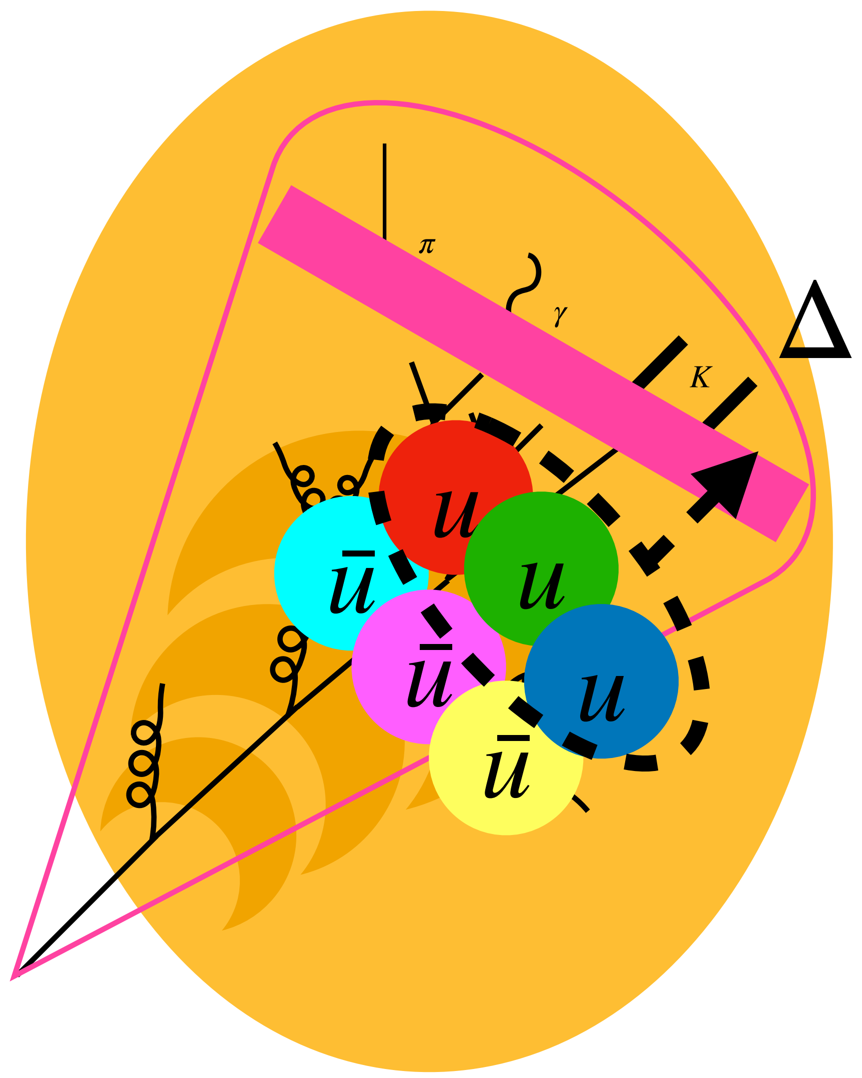
Observe: **No radius dependence of** R_{CP} within uncertainties.

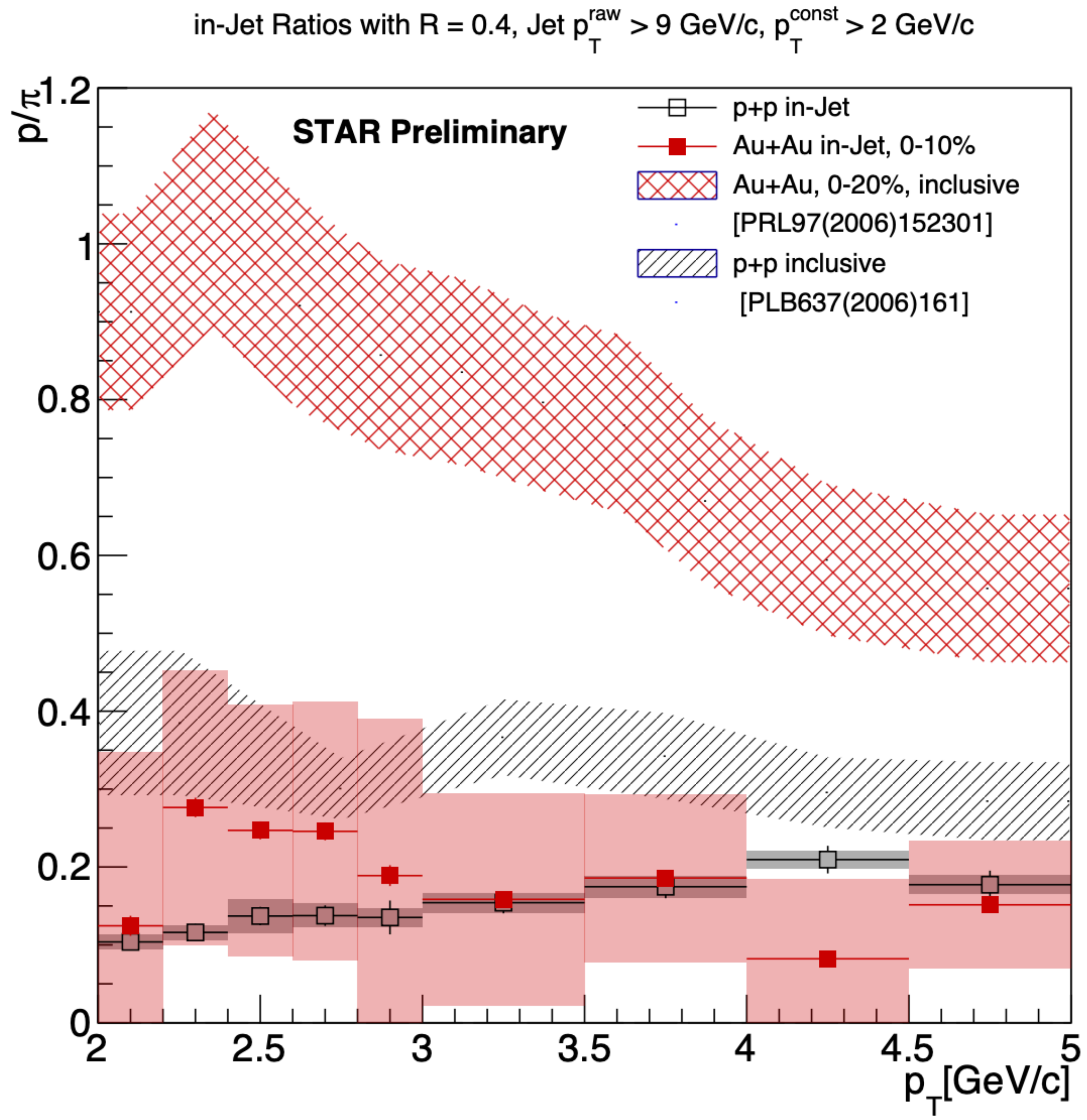
Agrees with models predicting minimal R-dependence of suppression.

Outlook: measuring generalized angularities

Searching for medium response





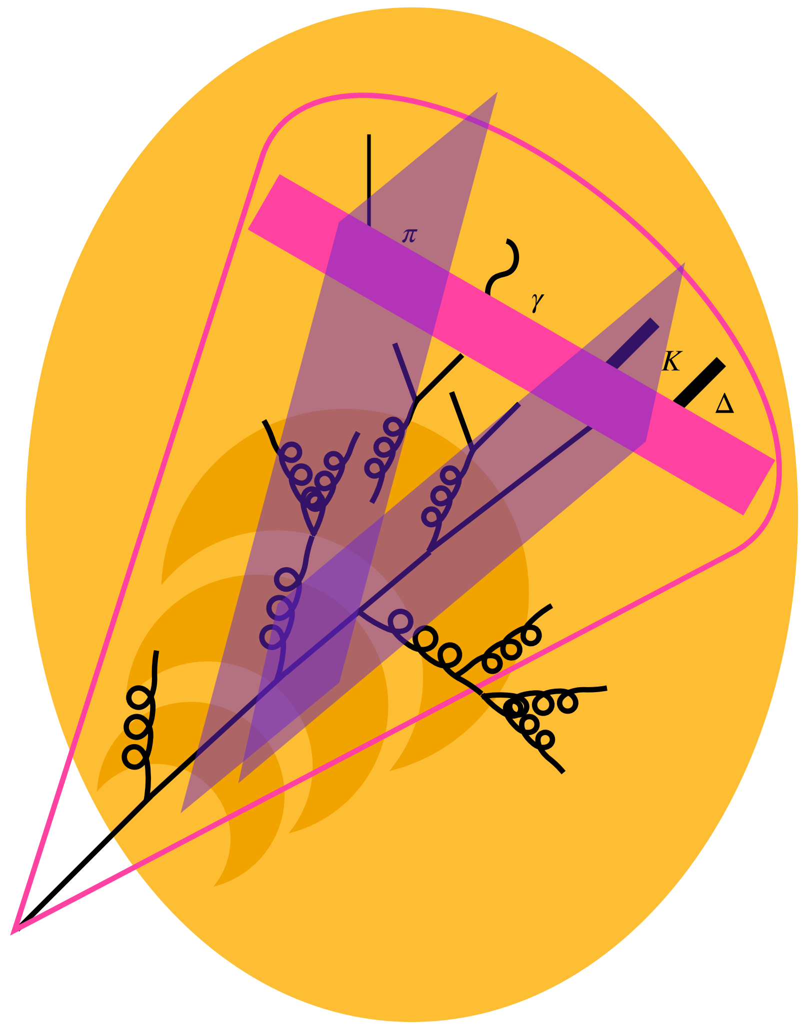


Possible expectation of *parton coalescence in jet*: enhanced baryon-to-meson ratio in A+A (left)

No observed modification of *in-jet* p/π ratio for $R = 0.2$ - 0.4 jets, after extension to lower constituent threshold (right)

<u>Outlook</u>: finalizing for publication in near future

Physics from the STAR jet program



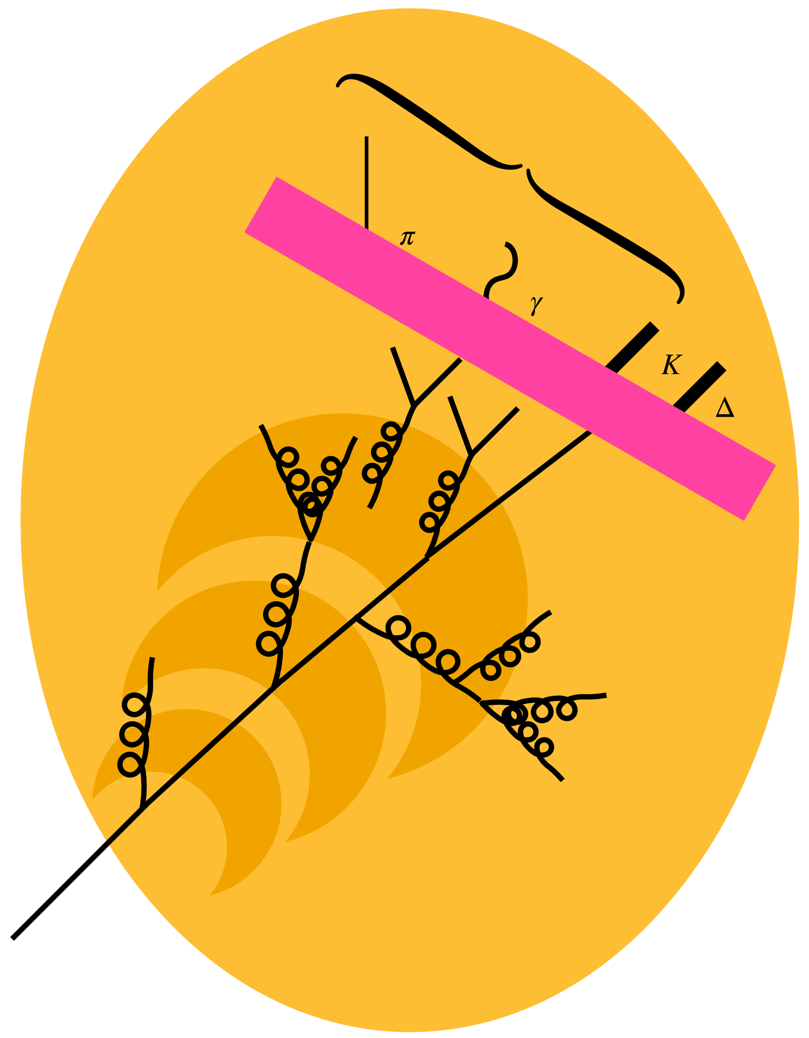
Pathlength dependence of energy loss

Suppression of jets with hard-fragmenting charm hadrons

Medium-induced modification of substructure not observed

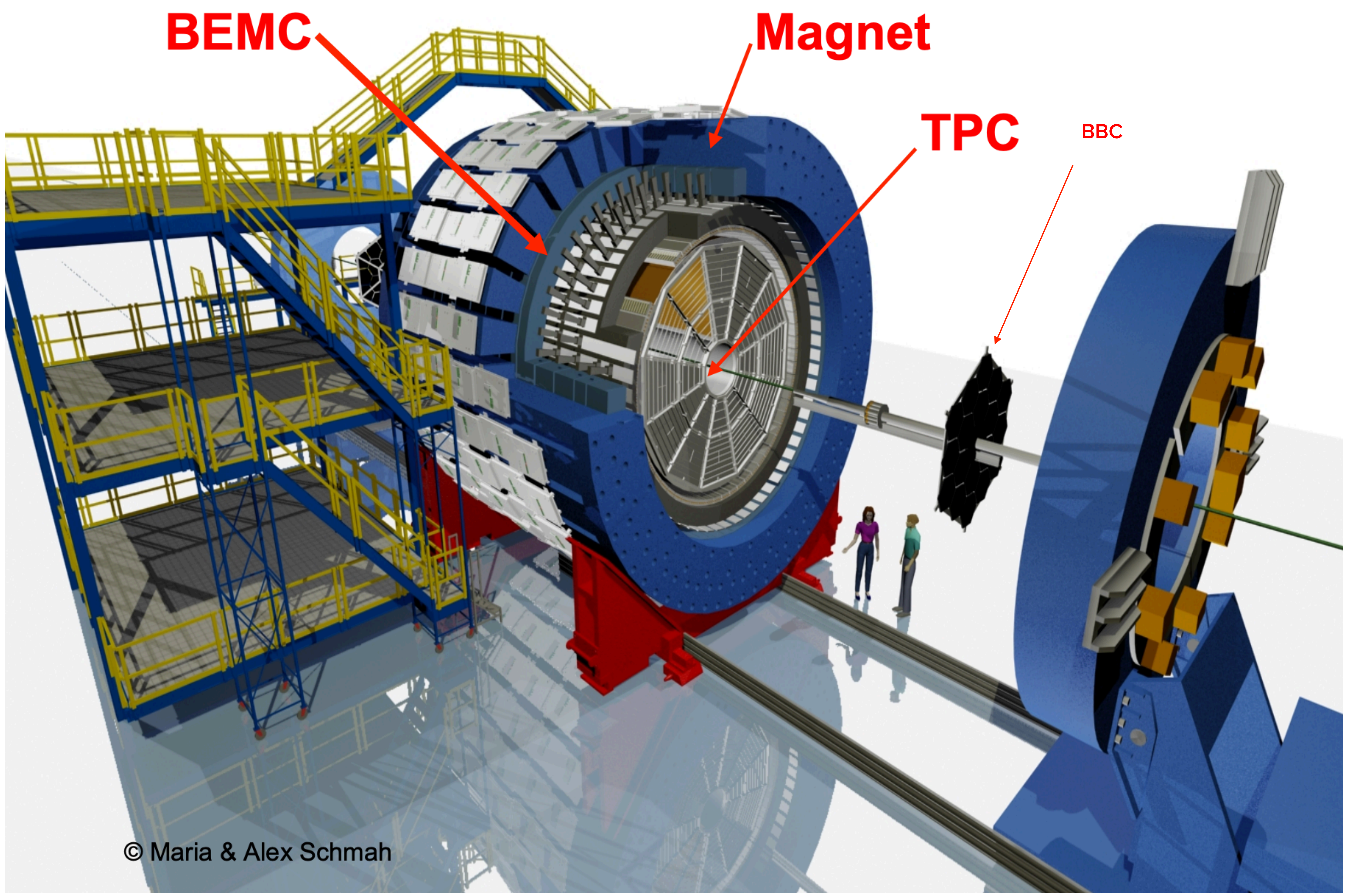
Testing limits of models' description of charge flow of hadronization

Medium-induced hadrochemistry effect not observed in jets



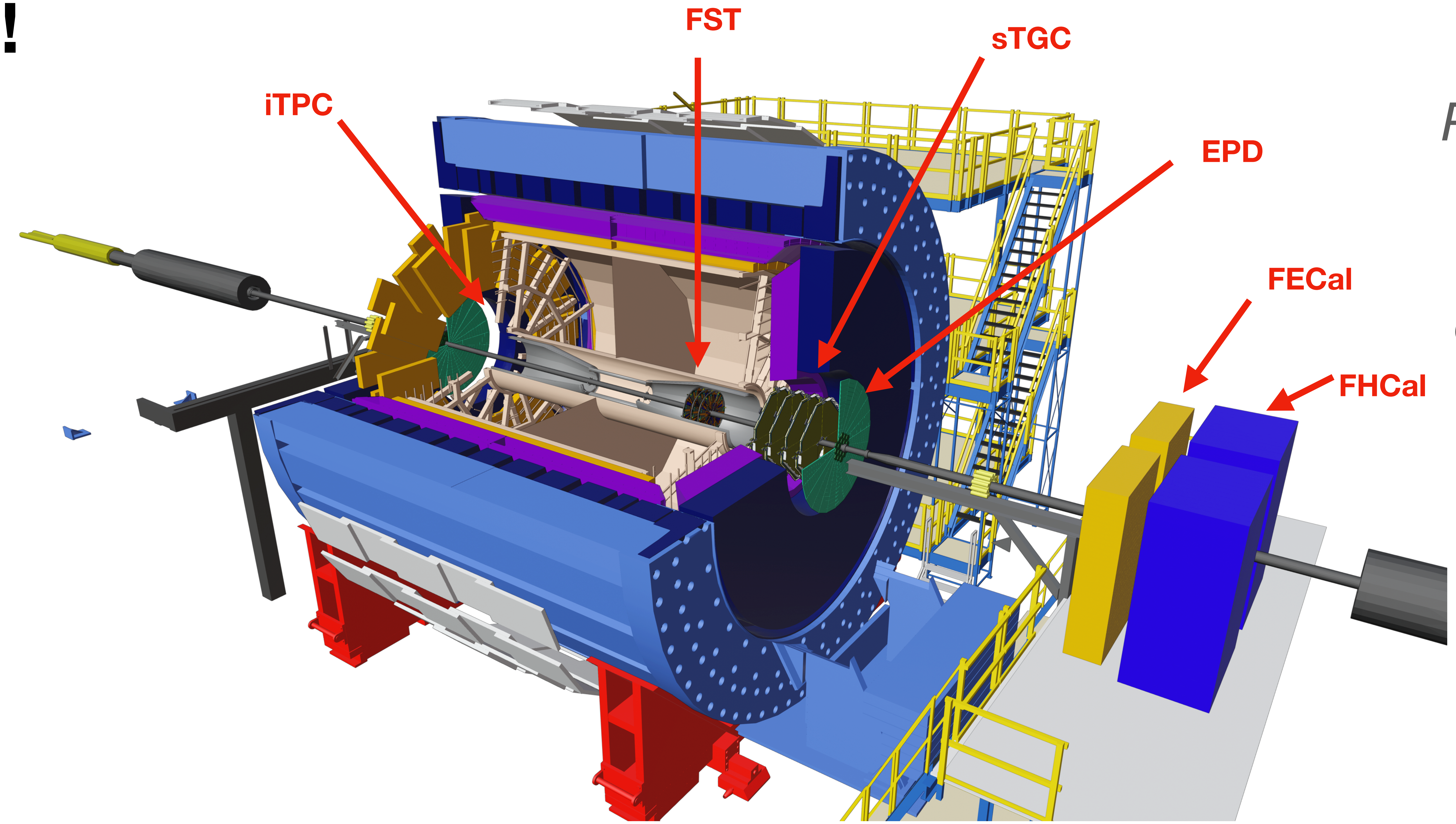
Hard probes at STAR

In the 2010s



Hard probes at STAR

In the 2020s!



Precision tracking

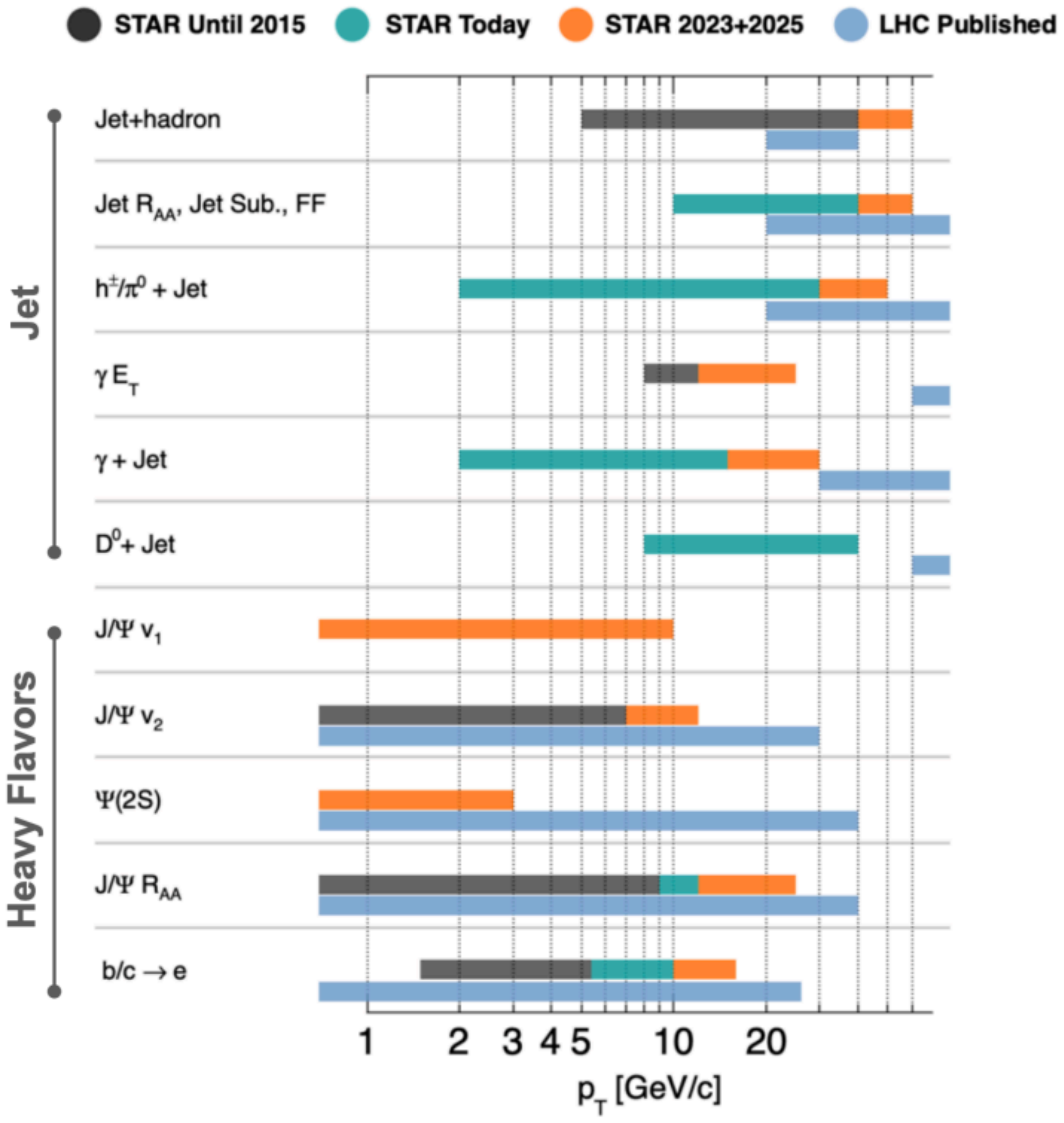
Forward jets → different x; q v. g

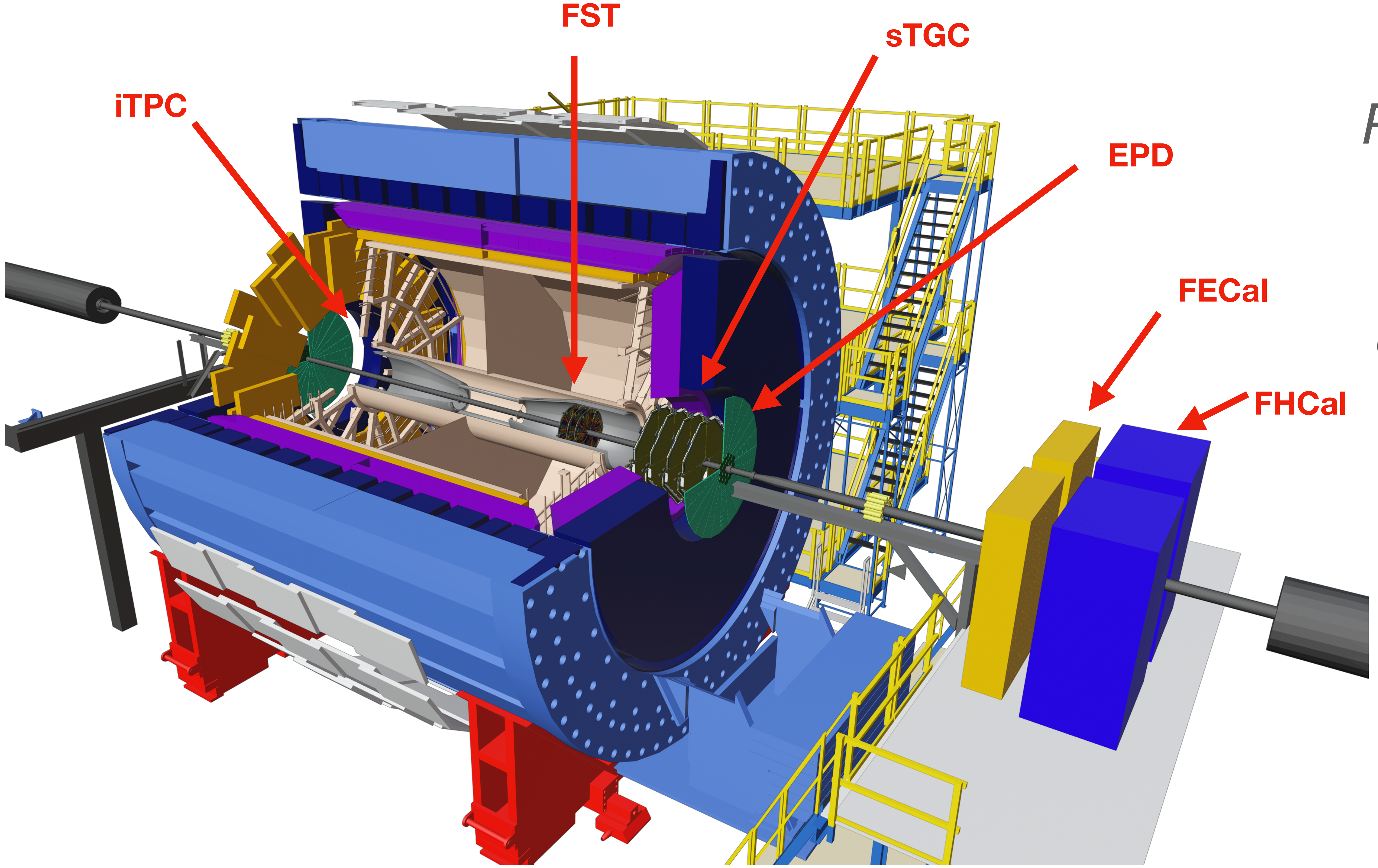
Unbiased centrality/EP determination

DAQ rate: 5 kHz

Hard probes at STAR

In the 2020s!





Precision tracking

Forward jets → different x; q v. g

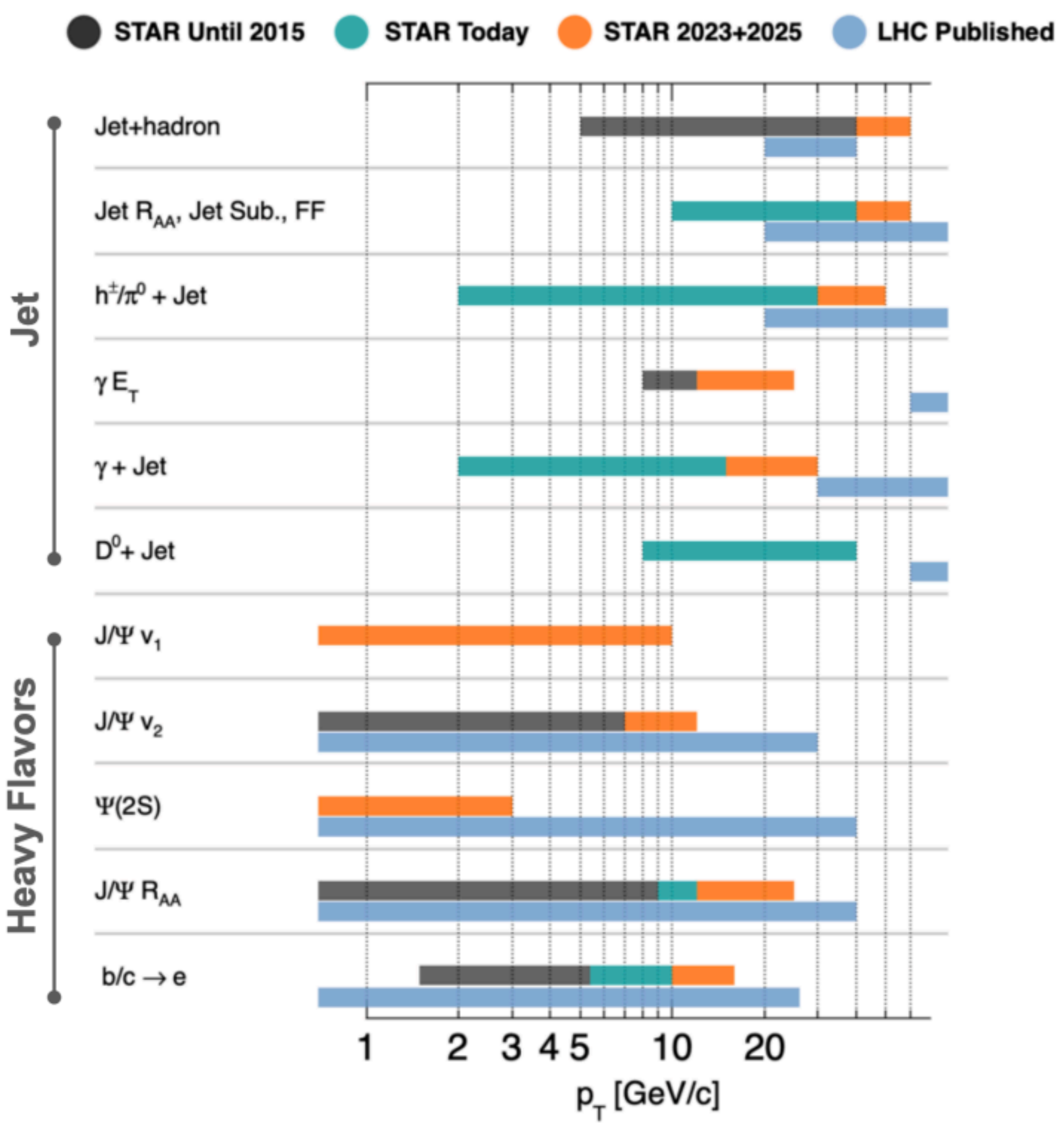
Unbiased centrality/EP determination

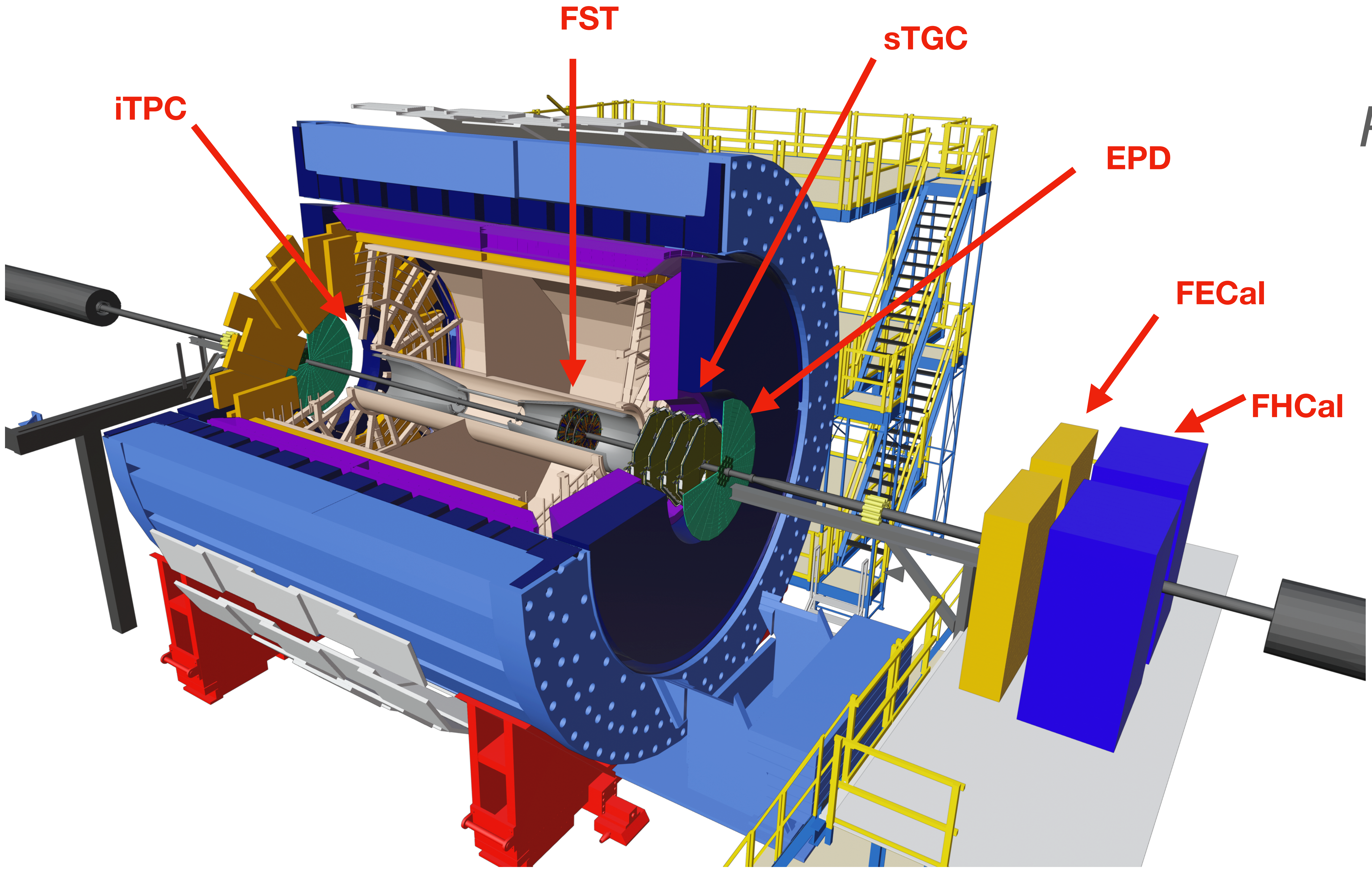
DAQ rate: 5 kHz

Runs 23 (Au+Au) & 24 (pp): Took 872 μb^{-1} and 168 pb^{-1} of high-p_T triggers

Hard probes at STAR

In the 2020s!





Precision tracking

Forward jets → different x; q v. g

Unbiased centrality/EP determination

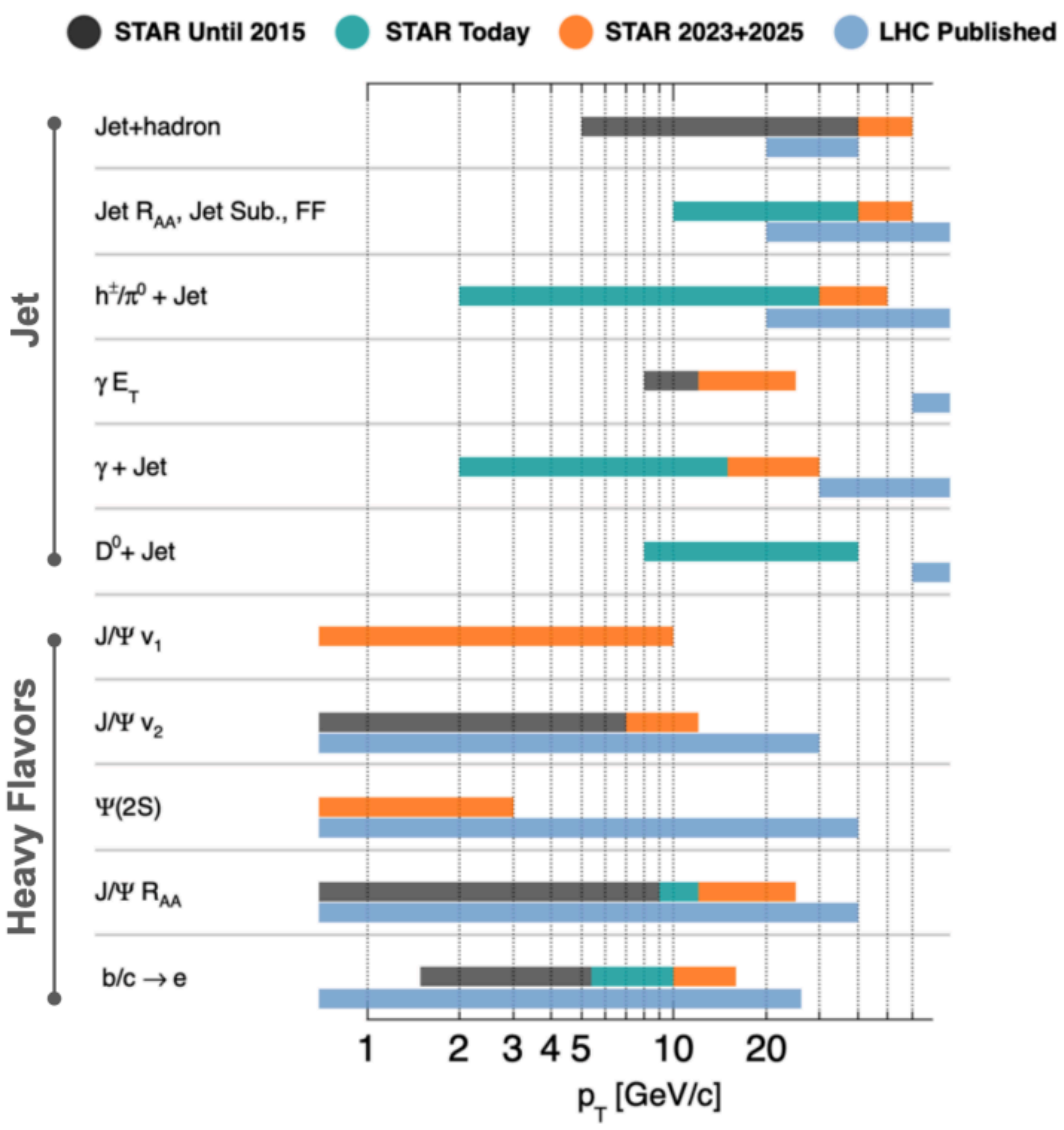
DAQ rate: 5 kHz

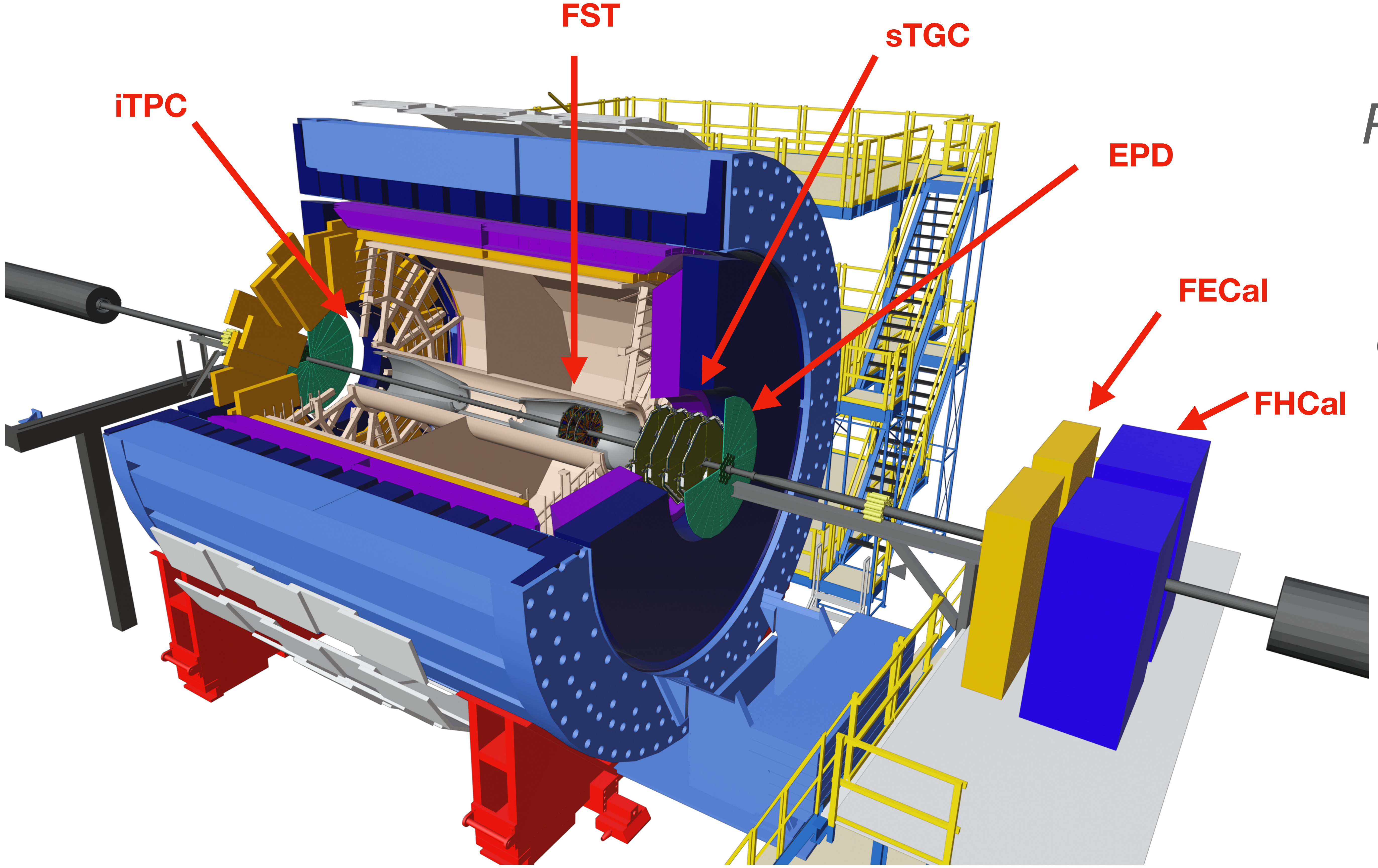
Runs 23 + 25[1,2]: expected $\sim 3\times$ increase in statistics for hard probes measurements relative to current Au+Au analyses w/ Run 14 → improved uncertainties & **kinematic reach** / **overlap w/ LHC**

[1] SN0793
[2] SN0819

Hard probes at STAR

In the 2020s!





Precision tracking

Forward jets → different x; q v. g

Unbiased centrality/EP determination

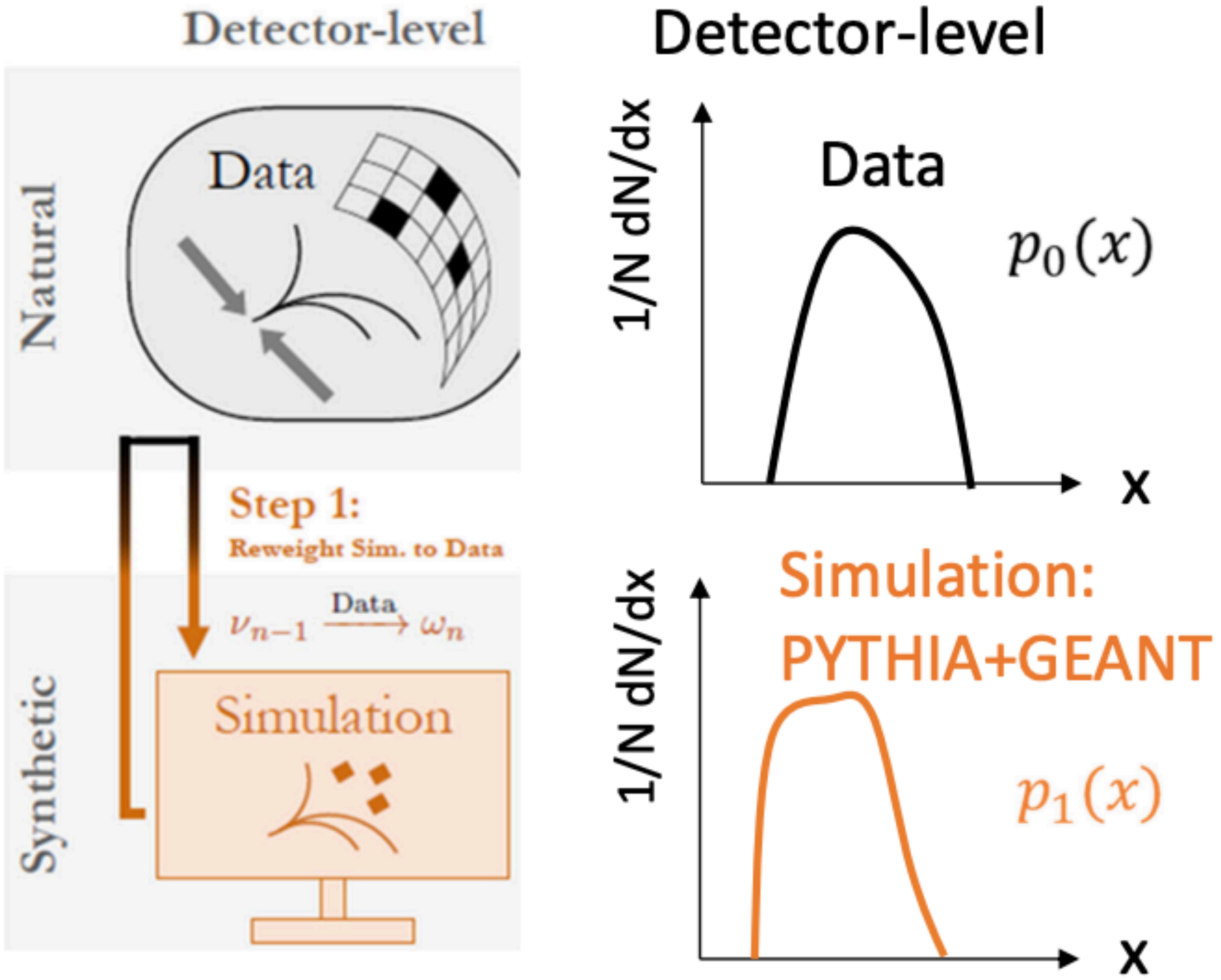
DAQ rate: 5 kHz

Run 25^{++}*?* Opportunity if goals met to take pAu data with upgrades!

Thank you!

MultiFold

Method: machine learning



E.g., Iteration 1, step 1:

Weights: $w(x) = p_0(x)/p_1(x)$ Ok for 1D

$$\approx f(x)/(1-f(x))$$ (Andreassen and Nachman PRD 101, 091901 (2020))

where f(x) is a neural network and trained with the binary cross-entropy loss function

to distinguish jets coming from data vs from simulation

Where does the machine learning part come in?

Unfolding → Reweighting histograms → Classification → Neural network

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MultiFold

Method: machine learning

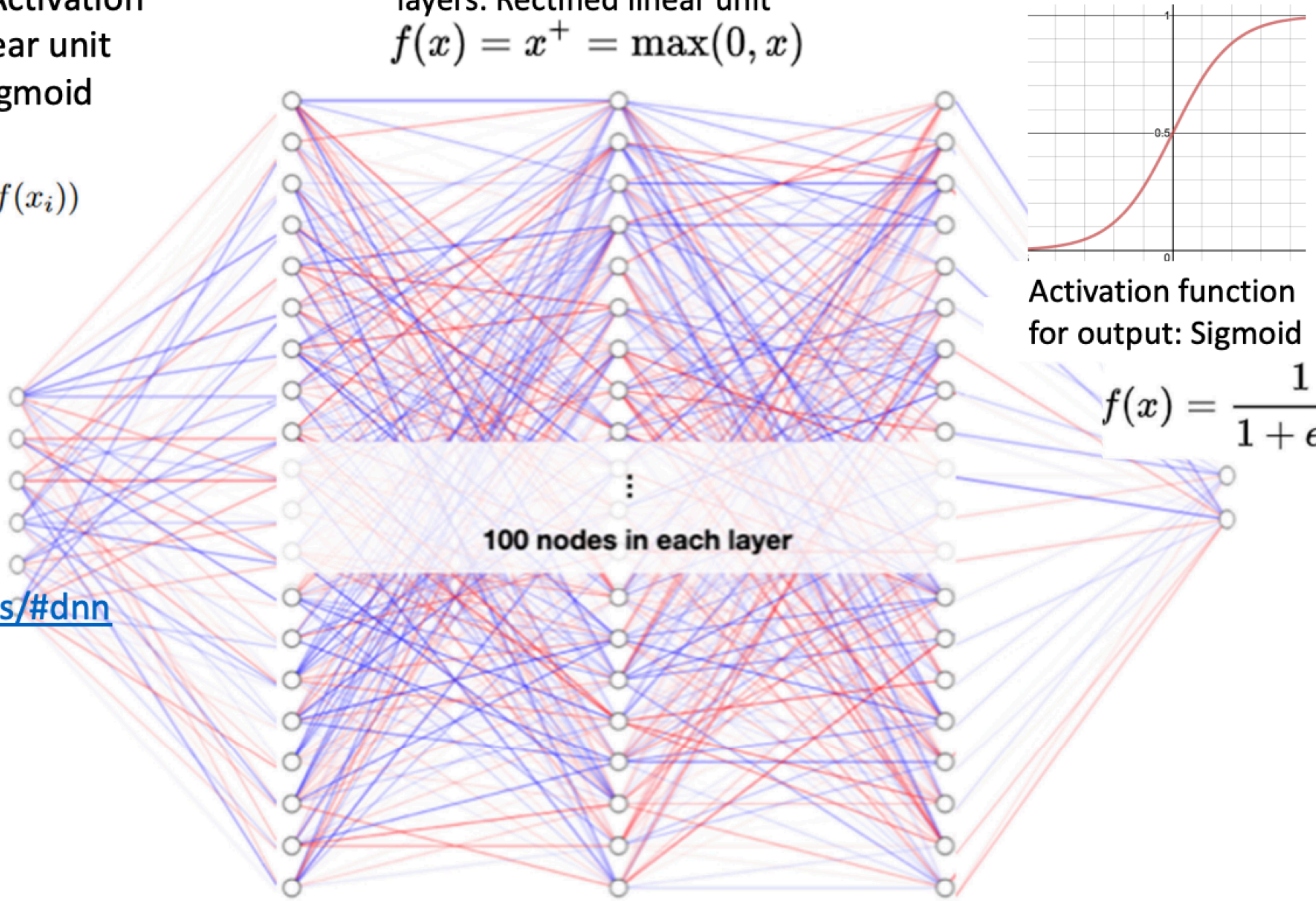
- Architechture: Dense neural network Activation function for dense layers: Rectified linear unit
- Activation function for output layer: Sigmoid
- Loss function: Binary cross entropy

$$\mathrm{loss}(f(x)) = -\sum_{i\in 0} \log f(x_i) - \sum_{i\in 1} \log(1 - f(x_i))$$

- Optimization algorithm: Adam https://arxiv.org/pdf/1412.6980.pdf
- Nodes per dense layer: [100,100,100]
- Output dimension: 2
- Input dimension: 6
- All hyperparameters are default: https://energyflow.network/docs/archs/#dnn

Activation function for dense layers: Rectified linear unit

$$f(x) = x^+ = \max(0, x)$$



Activation function for output: Sigmoid

$$f(x) = \frac{1}{1+e^{-x}}$$

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